



Control Plane Strategies for Elastic Optical Networks

Turus, Ioan

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Turus, I. (2015). *Control Plane Strategies for Elastic Optical Networks*. Technical University of Denmark.

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Control Plane Strategies for Elastic Optical Networks

Ioan Turus

January 2015



NORDUnet A/S
Kastruplundgade 22
2770 Kastrup
Denmark



Networks Technologies and Service Platforms
DTU Fotonik
Technical University of Denmark
Ørstedes Plads 343
2800 Kgs. Lyngby
Denmark

Preface

This thesis presents a selection of the research work performed during the Industrial Ph.d. study from 1st of January 2012 until 31st of December 2014.

The project was conducted in collaboration with Networks Technology and Service Platforms group at the Department of Photonics Engineering, Technical University of Denmark (DTU) and NORDUnet A/S, under the supervision of Professor Lars Dittmann, Ph.d., Researcher Anna Manolova Fagertun, Ph.d., and NORDUnet Chief Development Officer Josva Kleist, Ph.d.

The research presented in this thesis deals with the novel concept of elastic optical networks, the control plane implementations in support of elastic optical networks, as well as strategies for enhancing the energy efficiency in optical transport networks. The thesis consists of an introductory part to elastic optical networks and control plane implementation, a description of the methodology used for performing the research and a concluding part. Following the conclusions are the nine manuscripts prepared during the course of the Ph.d. study.

A six-month external research stay took place at Bell Laboratories, Alcatel-Lucent in Paris, France, under the supervision of Dr. Annalisa Morea.

This Ph.d. study, the external research stay and participation in international conferences were co-financed by the Danish Ministry of Higher Education and Science (Uddannelses- og Forskningsministeriet) and NORDUnet A/S, while access to simulation licenses and documentation was provided by the Technical University of Denmark (DTU).

Lyngby, 22nd of January 2015

Ioan Turus

Summary

The goal of this Ph.d. project is to present and address selected challenges related to the increasing traffic demand and limited available capacity in core optical fiber infrastructure in parallel with tighter requirements of reducing energy consumption and operational costs.

Elastic Optical Networks (EONs) concept is proposed as a solution to enable a more flexible handling of the optical capacity and allows an increase of available capacity over the existing optical infrastructure.

One main requirement for enabling EONs is to have a flexible spectrum structure (i.e. Flex-Grid) which allows the spectrum to be used as an on-demand resource. Flex-Grid raises new challenges for controlling the dynamic spectrum slots environment. This thesis addresses, as part of the Celtic project “Elastic Optical Networks” (EO-Net), the control of Flex-Grid architectures by extending the capabilities of a GMPLS (Generalized Multi-Protocol Label Switching)-based control framework in accordance with existing IETF standards and recommendations.

The usual approach of extending capacity in transport networks by incrementally adding more optical resources results in a very inefficient usage and determines a high power consumption. EONs offer the opportunity of deploying energy efficiency strategies, which benefit from the flexible nature of elastic optoelectronic devices. This thesis proposes and investigates different approaches for reducing power consumption based on EONs in realistic dynamic traffic scenarios.

Resumé

Målet for denne Ph.d. afhandling er at præsentere og behandle udvalgte udfordringer i forbindelse med den øgede mængde trafikmængde og begrænsede tilgængelige kapacitet i backbone optiske fiberinfrastrukturer set i lyset af behovet for at begrænse energiforbruget og de operationelle udgifter.

Elastiske Optiske Netværk (EON) er koncept, der er foreslået som en måde at give en mere fleksibel håndtering af optisk kapacitet og således muliggøre en mere effektiv udnyttelse af kapaciteten i eksisterende optiske infrastrukturer.

EON forudsætter en fleksibel struktur af det optiske spektrum (kaldet Flex-Grid) som tillader at spektrum kan anvendes efter behov. I Flex-Grid netværk er det en udfordring at kontrollere den dynamiske tildeling af spektrum. Denne afhandling undersøger, som del af "Celtic projektet om Elastisk Optiske Netværk", hvorledes Flex-Grid kan kontrolleres via udvidelser af "Generalized Multi-Protocol Label Switching" (GMPLS) i henhold til IETF standarder og anbefalinger.

Traditionel udvidelse af transport netværk sket ved gradvist tilføjelse af optiske ressourcer; dette har resulteret i en meget ineffektiv udnyttelse og et uforholdsmæssigt højt energiforbrug. Den fleksibilitet, der følger ved brug EON, gør det muligt at anvende mere energi effektive strategier i de optisk-elektroniske kredsløb. Denne afhandling foreslår og undersøger EON strategier i forskellige virkelige dynamiske trafik senarier med henblik at nedbringe energiforbruget.

Acknowledgements

The three years of a wonderful and unique journey made my Ph.d. study come to an end. During this time, I have had the honor to meet, collaborate, work, discuss, and debate with dedicated and inspiring people. I would like to thank the following people for their support and invaluable assistance they provided during the research study.

First and foremost, I thank my supervisors Lars Dittmann from DTU and Josva Kleist from NORDUnet for their continuous support and encouragement throughout this thesis.

I am especially grateful to Anna Manolova Fagertun for her collaboration and continuous help in performing my research while always providing me clarity on the research path towards achieving the goals.

A special thanks to Annalisa Morea who guided me during the external research stay at Bell Laboratories, Alcatel-Lucent in Paris. I consider that working with Annalisa was a great chance and a great source of inspiration.

I would like to thank to Rasmus Lund, Alberto Colmenero, Large Lange Bjørn and the other great colleagues at NORDUnet for their support in performing the research work, introducing me on industrial aspects as well as making the three years office sharing in Kastrup being an example of a great work environment.

I thank Dominique Verchere from Alcatel-Lucent Bell Labs in Paris who enlightened me with specific aspects of network protocols while providing important feedback on the protocol implementations. I also want to thank Nihel Benzaoui and the rest of colleagues from Alcatel-Lucent Paris who made my external stay a unique and lovely experience while placing Paris and France in the top of my wish-to-go destinations list.

I would also like to acknowledge Francesco da Ros, Silvia Saldana Cercos, Aleksandra Checko, Cosmin Caba as well as the other colleagues from DTU Fotonik for their valuable input, discussions and great time we spent together inside and outside DTU.

A special thanks to my great friends: Georgious Tologlou, Jorge Lopez Vizcaino, Vlad Acretoaie and Theodoros Ntouvalis who have been of great help and always present with advices, support and understanding. Thank you for being my friends!

And last, but not least, I would like to mention my family – my mother, my father and my sister - who were always supportive and kind while giving me the confidence and inspiration starting already 20 years ago at the beginning of the academic career. I also thank my uncle, my aunt, and my cousin for being there whenever I needed their help. I would also like to mention my grandparents who were always giving their best and sometimes even more for their grandson's personal development. Despite that my two grandfathers left during these years, I will never forget their advices and the

moments spent together discussing the experiences of a Ph.d. I would have never reached this point without my family's continuous support.

Finally, it has been an extraordinary experience and a great chance to have all of you around during my Ph.d. study.

Papers included in the thesis

- [A] I. Turus, A. M. Fagertun and L. Dittmann. GMPLS control plane extensions in support of Flex-Grid enabled elastic optical networks. In proceedings of OPNETWORK 2013 Conference, Washington, D.C.
- [B] I. Turus, J. Kleist, A. M. Fagertun and L. Dittmann. Evaluation of strategies for dynamic routing algorithms in support of Flex-Grid based GMPLS elastic optical networks. In Proceedings of 39th European Conference and Exhibition on Optical Communication (ECOC 2013), London, UK.
- [C] I. Turus, A. Morea, D. Verchere, A. M. Fagertun, L. Dittmann and J. Kleist. Traffic-aware Elastic Optical Networks to leverage Energy Savings. In proceedings of 6th Latin-American Conference on Communications (LATINCOM 2014), Cartagena de Indias, Colombia.
- [D] I. Turus, A. Morea, D. Verchere, A. M. Fagertun, L. Dittmann and J. Kleist. Energy savings in dynamic and resilient optical networks based on traffic-aware strategies. In Proceedings of 16th International Telecommunications Network Strategy and Planning Symposium (Networks 2014), Funchal, Portugal.
- [E] I. Turus, A. Morea, D. Verchere, A. M. Fagertun, L. Dittmann and J. Kleist. Power efficient service differentiation based on traffic-aware survivable elastic optical networks. In Proceedings of 6th International Workshop on Reliable Networks Design and Modeling (RNDM 2014), Barcelona, Spain.
- [F] I. Turus, A.M. Fagertun and J. Kleist. OPEX savings based on energy efficient strategies in NREN Core Optical Networks. Presented at 28th NORDUnet Conference, 2014, Uppsala, Sweden.

Presentations and extended abstracts

- [G] I. Turus, J. Kleist and A. M. Fagertun. Flex-Grid architecture for NREN optical networks. Extended abstract in proceedings of TERENA Networking Conference 2014, Dublin, Ireland.

Ongoing work

- [H] I. Turus, A. M. Fagertun, L. Dittmann and J. Kleist. Evaluation of Distributed Spectrum Allocation Algorithms for GMPLS Elastic Optical Networks.
- [I] I. Turus, A. M. Fagertun, L. Dittmann and J. Kleist. Spectrum defragmentation based on Hitless Network Re-Optimization with RSVP-TE in GMPLS-based Flexible Optical Networks.

Contents

Preface.....	i
Summary	iii
Resumé.....	v
Acknowledgements.....	vii
Papers included in the thesis	ix
List of figures.....	xiii
List of tables.....	xv
I. Thesis structure	17
1. Introduction.....	17
1.1. Objectives	18
1.2. Thesis overview	18
2. Contributions.....	21
II. Theoretical background	27
3. Motivation.....	27
3.1. Communication systems and network infrastructures	27
3.2. Changes in today's network traffic.....	29
3.3. NORDUnet optical transport network	35
3.3.1 The NORDUnet transmission network	36
4. Elastic Optical Networks	39
4.1. Elastic Optoelectronic Devices.....	43
4.2. Flexible grid.....	47
5. Control planes for Elastic Optical Networks	51
5.1. Distributed control plane	51
5.1.1 Routing and Open Shortest Path – Traffic Engineering (OSPS-TE)	51
5.1.2 Resource ReserVation Protocol – Traffic Engineering (RSVP-TE)	55
5.1.3 Routing Modulation and Spectrum Assignment (RMSA)	57
5.2. Software Defined Networks and centralized control plane architecture ...	61
5.3. Energy efficiency based on Elastic Optical Networks	65
III. Methodology	71
IV. Conclusions and Outlook	75

Appendices.....	81
A. GMPLS control plane extensions in support of Flex-Grid enabled elastic optical networks.....	81
B. Evaluation of strategies for dynamic routing algorithms in support of Flex-Grid based GMPLS elastic optical networks	91
C. Traffic-aware Elastic Optical Networks to leverage Energy Savings	97
D. Energy savings in dynamic and resilient optical networks based on traffic-aware strategies	105
E. Power efficient service differentiation based on traffic-aware survivable elastic optical networks	113
F. OPEX savings based on energy efficient strategies in NREN Core Optical Networks	121
G. Evaluation of Flex-Grid architecture for NREN optical networks	129
H. Evaluation of Distributed Spectrum Allocation Algorithms for GMPLS Elastic Optical Networks	135
I. Spectrum defragmentation based on Hitless Network Re-Optimization with RSVP-TE in GMPLS-based Flexible Optical Networks	143
Bibliography	151
List of Acronyms	159

List of figures

Figure 1. Today's common network architecture	27
Figure 2. Traffic growth according to Cisco VNI [3]	29
Figure 3. Video Minutes per Viewer vs. increased speed of Fixed Broadband connections	30
Figure 4. Online video traffic growth forecasts depending on the time of the day	30
Figure 5. Weekly traffic variation measured in 1 st of Sept 2014 for aggregated NORDUnet traffic with Customers [4]	31
Figure 6. Novel access network technologies and applications driving traffic increase	32
Figure 7. Electricity demand in ICT industry and physical limitation of electricity production [7]	33
Figure 8. Highly dynamic variation of the optical connection parameters	33
Figure 9. NORDUnet Optical Transport Network [8]	35
Figure 10. The NORDUnet transmission network	36
Figure 11. The NORDUnet future network	38
Figure 12. Elastic optical network components	39
Figure 13. Flex-Grid architecture and slice definition	47
Figure 14. OSPF-TE advertisements in GMPLS control plane	52
Figure 15. Advertising Flex-Grid information via OSPF-TE	52
Figure 16. A Traffic Engineering Link Local LSA format	53
Figure 17. Type 1 sub-TLV showing a Bit Map format encoding of Flex-Grid information within OSPF-TE LSAs	54
Figure 18. RSVP-TE signaling in GMPLS control plane	55
Figure 19. The Flexi-Grid label encoding	56
Figure 20. Centralized Spectrum Assignment	58
Figure 21. Distributed Spectrum Assignment	58
Figure 22. SDN architecture	62
Figure 23. Structure of energy consumption in an operator's network [87]	65
Figure 24. Daily traffic variations measured for different network operators [90]	67
Figure 25. Sleep-modes transition for opto-electronic devices	68

Figure 26. Reduction of power consumption due to sleep-mode of regenerators during night time.	69
Figure 27. Reduction of power consumption due to rate adaptation of optoelectronic devices during night time.....	70

List of tables

Table 1. 100Gb/s PDM-QPSK available modulation format configuration [16]	44
Table 2. Grid and channel spacing values in a flexi-grid architecture.....	56

I. Thesis structure

1. Introduction

The core transport networks nowadays are dominated by optical transmission systems. There are various challenges experienced in optical transport networks today such as: a constant increase in the amount of transported traffic, a change from homogeneous to more heterogeneous characteristics of the requested optical connections and the physical limitation of the optical fiber in terms of available capacity. Moreover, since ICT is expected to reach 3% of the global CO₂ emissions by 2020 [1], there is a significant interest towards designing more efficient optical infrastructure.

A recently proposed solution to cope on short to medium term with the current challenges is the concept of elastic optical networks (EONs). EONs are based on the idea of enabling flexibility for different parameters associated to an optical connection such as: modulation format, symbol-rate, channel spacing, or forward error correction code (FEC). The main advantage and novelty brought by EONs is the ability to adapt the configuration of an optical channel to the specific requirements of a connection. Hence, by tuning the optical resources to the demand's specifications, the transport network can act proactively when facing the future traffic demands. Moreover, dynamic reconfigurations are possible and they can address the traffic growth and predictable traffic fluctuations, which are a common characteristic for aggregated core transport links.

In order to implement EONs capabilities on operational core optical networks, a set of challenges have to be addressed such as: the development and the standardization of elastic optoelectronic devices, the development of a control plane capable of handling elastic connections, as well as strategies for enhanced operations and power consumption optimization. Part of the work performed in this thesis was supported by the Elastic Optical Networks (EO-Net) Celtic project [2] where the different challenges related to the introductions of EONs were addressed.

The introduction of flexible spectrum allocation, also called Flex-Grid, raises concerns regarding the scalability of a control framework in a dynamic elastic optical networks environment. In this thesis two protocols namely RSVP-TE (Resource Reservation Protocol – Traffic Engineering) and OSPF-TE (Open Shortest Path First – Traffic Engineering) are analyzed and extensions are proposed, implemented and evaluated in support of a Flex-Grid enabled architecture. The control plane framework considers a distributed GMPLS-based control plane implementation.

Energy efficiency is an aspect widely studied in the past years at all network layers. Since the capacity challenges in core infrastructure started becoming an issue in the near past, the solution of providing extra capacity by incrementally adding more

optical resources is not scalable and it significantly impacts the power consumption and energy efficiency of a core transport infrastructure. Hence, new strategies based on the newly provided EONs capabilities have to be proposed and implemented in order to extend the capacity potential of current transport networks while optimizing the energy efficiency.

1.1. Objectives

The objectives of this thesis are to address the current challenges raised by the introduction and implementation of elastic optical networks concept in today's network scenarios. Thus, the thesis follows the following research goals:

- Understand and evaluate the benefits and challenges of introducing elastic optical networks;
- Propose, implement and evaluate a control plane solution capable of handling elastic optical connections deployment with a focus on Flex-Grid architectures;
- Propose, implement and evaluate a set of energy saving strategies which make use of the capabilities of elastic optical networks and based on the previously proposed control plane solution;

1.2. Thesis overview

The thesis format is described by a list of publications structure consisting of 6 published research papers, one extended abstract and two ongoing research activities.

Part I, Chapter 1 introduces the objectives of this research study and provides an overview of the thesis. A brief description of the performed research work and results associated to each of the publications are provided in Chapter 2.

In **Part II**, the theoretical background behind the performed research study is detailed. Chapter 3 describes the current challenges in core optical transport networks as well as the need for introducing the concept of elastic optical networks. Chapter 4 reviews the technical details of elastic optical networks and introduces the Flex-Grid concept. In Chapter 5 the control plane implementations in support of elastic optical networks and Flex-Grid is detailed with an in-depth analysis of the GMPLS-based framework implementation and a review of software-defined networks (SDN)-based solutions. Chapter 5 introduces a set of approaches used for improving the energy efficiency based on elastic optical networks.

In **Part III**, the methodology involved in the current thesis is detailed while the work has been mainly performed using a software-based discrete event-driven network simulator.

Part IV concludes the research activities, analyses the achieved results and presents a set of observations for the studied challenges.

The thesis ends with the enlisted research articles in the **Appendices**.

2. Contributions

A brief description of the contribution within each of the published and ongoing work is provided as it follows. The detailed content associated to each publication and ongoing work is provided in the Appendices part of the thesis.

2.1. GMPLS control plane extensions in support of Flex-Grid enabled elastic optical networks

The work in this paper (Appendices, [A]) consists of detailing Flex-Grid extensions required for GMPLS implementation in OPNET Modeler – a discrete event-driven simulation tool. Thus, based on an initial distributed GMPLS control plane model available at DTU and implemented in OPNET Modeler, the focus was on developing and implementing additional extensions for the GMPLS protocol suite (RSVP-TE and OSPF-T). RSVP-TE extensions were implemented with the purpose of enabling the reservation of generalized labels format and corresponding spectrum slots selection procedures. OSPF-TE extensions were implemented with the purpose of enabling the creation of spectrum databases based on extended LSA (Link State Advertisement) sub-TLVs (Type Length Value fields) attributes. A set of distributed spectrum allocation schemes and strategies for dynamic routing algorithms in support of Flex-Grid optical networks were evaluated based on the implemented model while validating its functionality.

2.2. Evaluation of strategies for dynamic routing algorithms in support of Flex-Grid based GMPLS elastic optical networks

The work in this paper (Appendices, [B]) focused on implementing and evaluating the proposed OSPF-TE extensions within GMPLS framework in support of Flex-Grid optical networks. The simulations show that the bitmap format of the sub-TLVs in the OSPF-TE LSAs is preferable, due to the limited load on the control plane, while it does not compromise significantly the performance. Moreover, two routing strategies were proposed and they emphasize the importance of collecting information about spectrum statuses in Flex-Grid networks. After evaluated on the NSF (National Science Foundation) network topology, results show that the “relaxation graph” strategy is able to provide up to 15% lower blocking for less loaded network while the “weighted graph” strategy is able to provide up to 70% lower blocking.

2.3. Traffic-aware Elastic Optical Networks to leverage Energy Savings

The work in this paper (Appendices, [C]) is investigating possible energy savings, which can be provided by exploiting a traffic-aware elastic optical network in a predictable growing and fluctuating yearly traffic distribution. Hence, a GMPLS-based control plane is implemented while dedicated RSVP-TE protocol extensions (i.e. Trigger messages) enable a dynamic reconfiguration of the optical channels according to the traffic fluctuations. A set of strategies is proposed and they are based on sleep-mode capabilities and data-rate adaptation of optoelectronic devices as well as grooming optical channels based on foreseen traffic variation and elastic capabilities. Simulations show that energy reduction of up to 43% and 46% can be achieved in DT17 and COST37 network topology scenarios, respectively. Moreover, when using modulation format adaptation it can be observed that a higher efficiency (often higher compared to the efficiency of symbol-rate adaptation) of this strategy is achieved for larger networks (in terms of optical reach) due to a larger variation of the number of regenerators. The grooming approach is able to reduce even more the power consumption but its efficiency is dependent on the network topology. Thus, higher energy savings are possible for smaller network topologies, due to the fewer possible source-destination node pairs for the requested connections. When using a “mixed” adaptation (symbol-rate and modulation format) together with grooming – the highest energy savings are achieved at the expense of a more complex control plane. The interesting observation of this work is that in smaller networks, a good trade-off between control plane complexity and energy savings is to deploy only symbol-rate adaptation; while for larger networks, an optimum choice is to deploy mixed adaptation without a grooming procedure.

2.4. Energy savings in dynamic and resilient optical networks based on traffic-aware strategies

The work in this paper (Appendices, [D]) introduces the resiliency aspect to the traffic-aware elastic optical networks approach regarding the challenge of reducing energy consumption. The resiliency mechanism adds an extra source of lowering the energy efficiency in core optical networks. This is because more network capacity and a significant amount of extra optoelectronic devices have to be deployed. Hence, two scenarios describing protected and unprotected networks are compared and analyzed. Results show that when deploying symbol-rate adaptation higher energy savings are achieved in unprotected networks, while for protected networks the modulation format adaptation is a better choice. When deploying the more complex “mixed”

adaptation, 39% and 70% energy savings are achieved for unprotected and protected cases, respectively.

2.5. Power efficient service differentiation based on traffic-aware survivable elastic optical networks

The work in this paper (Appendices, [E]) adds to the previously listed research studies the case of differentiating services based on their associated class of protection. Thus, a power efficient service differentiation is proposed based on the elastic and sleep-mode capabilities, as well as grooming approach using elastic optoelectronic devices. This approach is compared with the classical solution of deploying the optical connections statically without elastic optical network capabilities. Four classes of services were defined: Platinum, Gold, Silver and Best Effort based on different 1+1 and 1:1 dedicated protection schemes. Simulations show that when no elastic capabilities are taken into account the ratio between the different service classes distribution highly influences the power consumption while Platinum and Silver demands are the most power hungry services. Moreover, when elastic capabilities are considered, the dependence of the power consumption on the service class distribution becomes negligible. Moreover, thanks to the introduction of a grooming mechanism, a higher Quality of Service (QoS) is enabled from the protection point of view to the Silver connection. This is because a Best-Effort connection can be transported over the protection section of a Silver connection when grooming conditions are met – hence, activating the operational mode for the idle devices associated to the Silver connection for a certain period.

2.6. OPEX savings based on energy efficient strategies in NREN Core Optical Networks

The work in this paper (Appendices, [F]) focuses on mapping the previously performed research studies into a realistic case of an existing NREN (National Research and Education Network) core optical infrastructure and opening up discussions and awareness of the energy efficiency and power consumption models within NREN community. Results of analyzing NORDUnet traffic pattern on aggregated links with customers show that when computing peak vs. average traffic, ideally 32%, 43% and 69% energy savings could be achieved on a daily, weekly and yearly basis, respectively. Within the energy savings achieved on a weekly basis, exclusively the drops in the traffic give 11% savings during the weekend. Within the energy savings achieved on a yearly basis, 26% are given exclusively by the yearly growth. Thus, it results that a significant opportunity for performing energy savings in

NREN core optical networks is available when enabling elastic optical networks for tuning the capacity and power consumption to the real traffic variation. Results show that up to 50% energy savings can be achieved in both NORDUnet and GEANT core optical networks. Moreover, it is observed that modulation format adaptation is significantly more efficient in the case of GEANT topology compared to symbol-rate adaptation, due to the existence of longer link spans.

2.7. Evaluation of Flex-Grid architecture for NREN optical networks

The work assigned to this extended abstract (Appendices, [G]) considered an in-depth evaluation of the impact that Flex-Grid technology reveals within current NRENs' core optical networks. Flex-Grid technology was suggested as a solution to cope with different challenges in NREN transport networks such as traffic increase as well as introduction of novel physical layer services. The work emphasized the different challenges faced by the introduction of Flex-Grid as well as possible solutions:

- an increased complexity and extension requirements for a GMPLS-based control plane;
- fragmentation problem and hitless de-fragmentation approaches;
- minimum channel width given by the limitation in electronic processing;
- dependency on the optical network topology;
- migration options from Fixed-Grid infrastructure to a Flex-Grid enabled one;
- introduction of new photonic services with special requirements supported by Flex-Grid: e.g. Frequency Transfer Application, Time Synchronization Application, High data-transfer between Data Centers, Transfer of Broadband Frequency;
- guard bands separations;

2.8. Evaluation of Distributed Spectrum Allocation Algorithms for GMPLS Elastic Optical Networks

The ongoing work in this paper (Appendices, [H]) focuses on investigating different spectrum assignment algorithms for the Flex-Grid elastic optical networks while using a GMPLS-based control plane. The control plane is deployed without routing features in order to emphasize the role of the spectrum allocation algorithms and the performance of the RSVP-TE proposed extensions. New allocation methods such as "SSbalanced" and "Metric balanced LP" are proposed and compared with classical First-Fit allocation method. Results show that "SSbalanced" method can reduce

fragmentation with up to 10% while blocking is reduced with 10% for low loaded network scenarios. “Metric balanced LP” provides better results in terms of fragmentation, which is reduced with 50% while blocking is similar with the First-Fit allocation case.

2.9. Spectrum defragmentation based on Hitless Network Re-Optimization with RSVP-TE in GMPLS-based Flexible Optical Networks

The ongoing work in this paper (Appendices, [II]) focuses on the problem of fragmentation which is characteristics to Flex-Grid enabled elastic optical networks. Hence, a solution is proposed to perform de-fragmentation based on modified RSVP-TE Refresh messages and between 3% and 25% improvement in connection blocking probability is achieved. The method uses RSVP-TE Refresh messages to collect the necessary information to re-allocate the channels with only few changes in the RSVP-TE signaling procedure. The method does not rely on OSPF-TE link state advertisements (LSAs) and hence, an overloaded control plane or the existence of decisions based on outdated routing information is avoided. Moreover, due to the possibility of re-tuning the transponder laser to a wider or tighter spectrum slice, the method is performed in a hitless manner and the connectivity is not interrupted during the re-configuration process.

II. Theoretical background

3. Motivation

3.1. Communication systems and network infrastructures

Communication systems nowadays represent a key aspect driving the evolution of the individual and organizational day-to-day life. Communication systems always rely on an infrastructure, which can vary from underground infrastructure (copper cables, fibers etc.), to air-based infrastructure (radio communications, etc.) or even rely on complex physics mechanisms such as quantum-based systems.

The infrastructure behind a communication system is often deployed by large public or private entities referred as network providers. A network provider can be often integrated into a popular Internet Service Provider (ISP) or have a dedicated activity on providing only connectivity to various foreign entities. The main service offered by a network provider is the network connectivity with specific properties varying from the type of infrastructure (wireless, wired etc.) to data capacity (e.g. going from a few kbps to several Gb/s) and down to advanced mechanisms for access control, monitoring etc.

From an architectural point of view, a network is often classified on a geographical manner spanning over different geographical areas while they are divided into the following three entities or layers (as depicted in Figure 1):

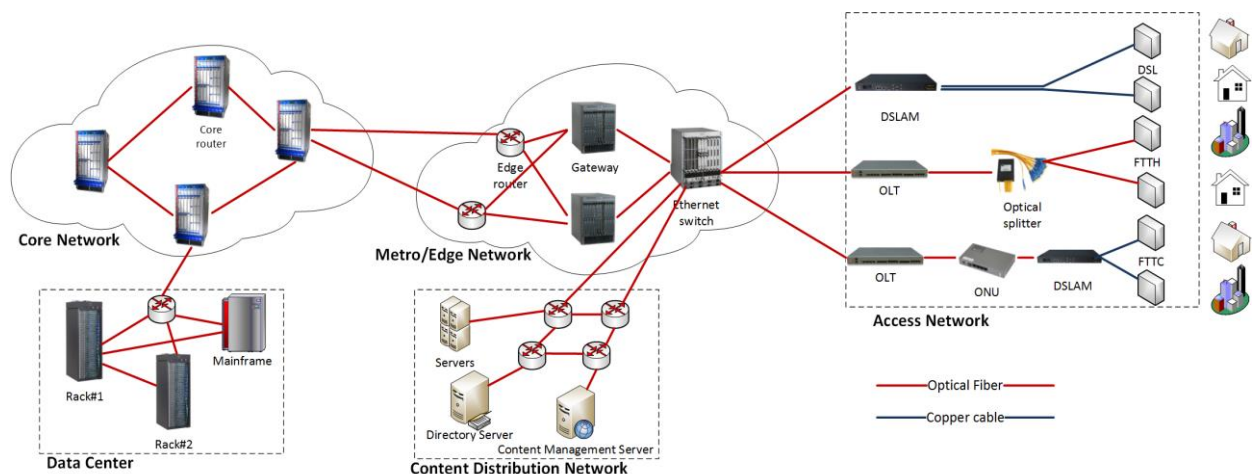


Figure 1. Today's common network architecture

- Core network – referring to a set of high capacity network resources (connections bandwidth ranging often above 1Gb/s, link lengths of hundreds of km and more, connections lifetimes often semi-permanent) which are optimized to exchange data received from metro elements and eventually connect to other infrastructures.
- Metro network – referring to a set of medium to high capacity network resources (connections bandwidth ranging often between a few Mb/s to a few Gb/s, link lengths ranging from a few hundred meters to a few km); it aggregates the data received from the access network elements and always forward it to other access network elements or aggregate and forward it to core network layer.
- Access network – referring to a set of low to medium capacity network resources (connections bandwidth smaller compared to metro and core networks, shorter link lengths and both semi-permanent and temporary connections lifetime) which connect directly to users (e.g. end devices, buildings, enterprises, houses, etc.); the access network entities are connected to metro network entities for higher-layer connectivity as well as to other access network elements.

The focus of this thesis is on the planning or operation of core network areas with already aggregated data links.

3.2. Changes in today's network traffic

Probably the main challenge present in today's core optical networks is the high and continuous traffic growth, which directly affects the revenue of the network operators. Indeed, the strong effect that the traffic growth has on the revenue comes from the decrease of the revenue per bit (the higher traffic has to be transported with a smaller cost per bit, i.e. 100Gb/s costs less than 10x10Gb/s).

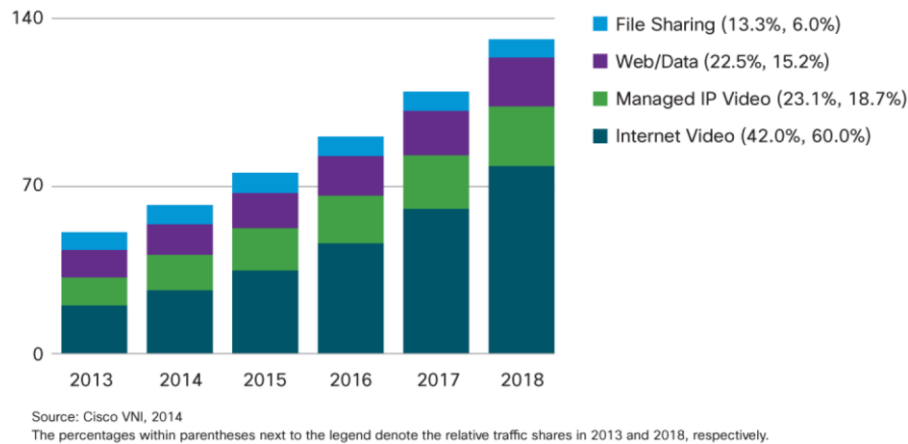
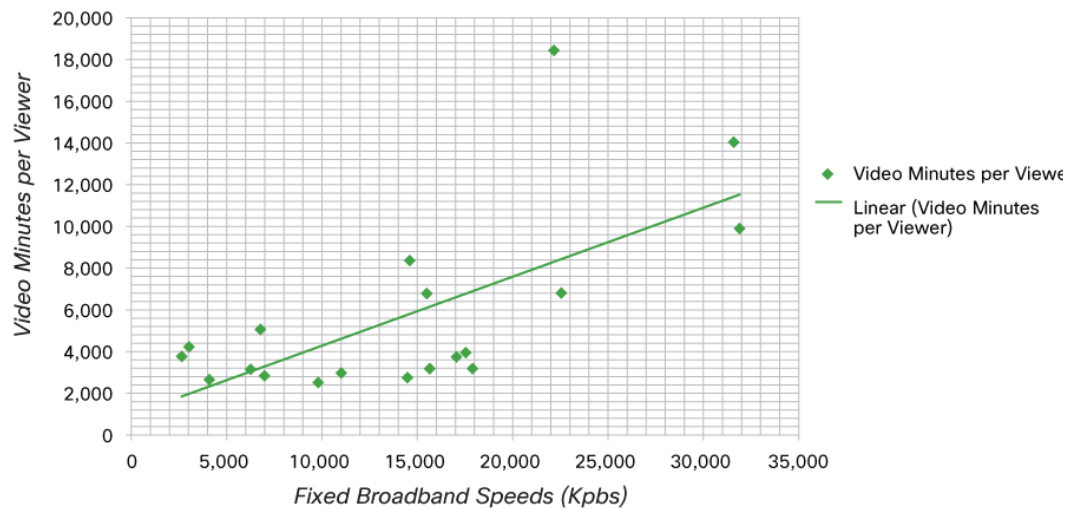


Figure 2. Traffic growth according to Cisco VNI [3]

Figure 2 shows the forecast for the overall Internet traffic growth: it triples between 2013 and 2018 [3]. It is important to note the data traffic partition: the higher traffic is expected to be associated to the Internet Video, which increases with 50% between 2013 and 2018. At the same time the total share of the Internet Video from the overall Internet traffic varies from 42% in 2013 to 60% in 2018. The File Sharing, Web/Data and Managed IP Video traffic types continue to grow as well but this growth is slower, hence they will decrease their share from the overall Internet traffic.

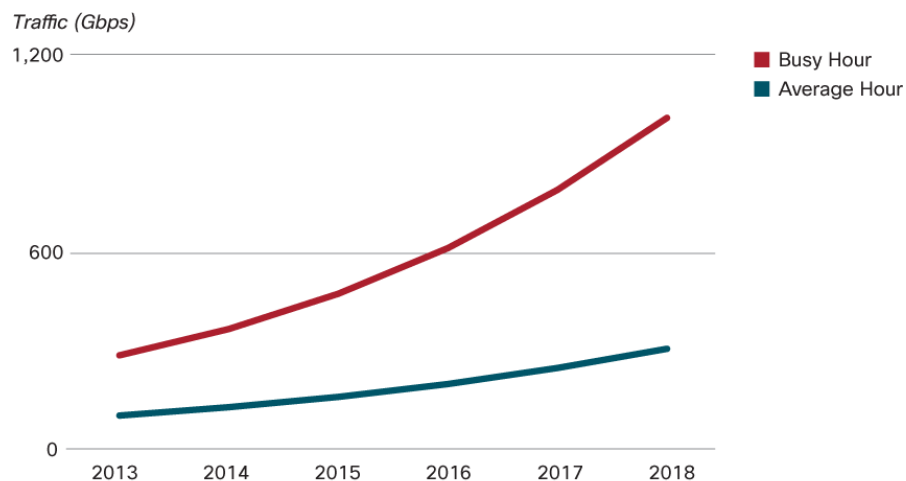
Moreover, in [3] a measurement shows that the amount of video (represented by the viewing time) consumed by users is increasing linearly with the increase in the speed of the fixed broadband connection (i.e. technology advance such as WDM PON) as shown in Figure 3. Indeed, video traffic represents one of the main drivers, which determine changes in the overall network requirements.



Source: Cisco VNI, 2014

Figure 3. Video Minutes per Viewer vs. increased speed of Fixed Broadband connections

Figure 4 shows another impact given by the traffic growth as studies in [3]. It has been observed that while the Internet traffic experiences a relatively constant growth pattern, during the busiest hour of a day the traffic growth is much higher compared to the average. The traffic growth in 2012 was 32% during the busiest hour compared to a 25% growth for the average traffic growth. This results in a more variable and dynamic traffic behavior, which in turns requires a more flexible way of providing the capacity to the user throughout current network infrastructures.



Source: Cisco VNI, 2014

Figure 4. Online video traffic growth forecasts depending on the time of the day

In Figure 5, the strong dynamic traffic behavior is emphasized in NORDUnet core network while measuring the aggregated NORDUnet traffic with its research and education networks customers. It can be observed that the traffic varies between less than 10Gb/s at minimum values up to more than 50Gb/s for the high peaks.

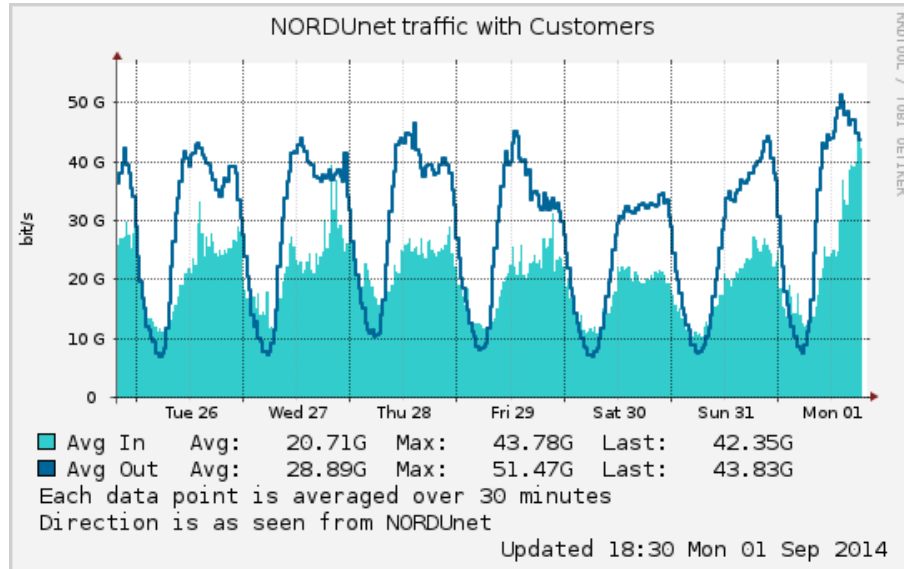


Figure 5. Weekly traffic variation measured in 1st of Sept 2014 for aggregated NORDUnet traffic with Customers [4]

Specifically for core networks, the traffic has experienced a 30-60% compound annual growth rate (CAGR) over the last two decades while it is estimated to continue growing at least with a similar trend [4].

The internet traffic growth can be explained by at least two main changes, which act at the interface between the user and the network:

- **Novel access technologies:**

The advances in the technology brought advanced solutions at the access network, which allow the users to access higher bandwidths at higher or similar price. Today, users are able to acquire a FTTH (Fiber-To-The-Home connectivity) or a VDSL (Very High bitrate Digital Subscriber Line) link, which could allow them to access the network at speeds up to 100 Mb/s or 20 Mb/s respectively. Moreover, the mobile connectivity allows now to reach bitrates up to 100Mbit/s thanks to the introduction of MIMO (Multiple-Input Multiple-Output) and OFDM (Orthogonal Frequency-Division Multiplexing) technologies and LTE/4G architecture.

- **Novel applications:**

In parallel with the network access technologies, new applications were developed over the network infrastructure thanks to the availability of higher bitrates. Various examples (as shown in Figure 6) such as Netflix – which allows broadcasting of HD

online video, 3D TV – broadcasting the London Olympics 2012, or even highly specialized medical applications which require the transfer of high resolution radiograms. An example of the impact of novel applications (i.e. Netflix) in the business model of a network provider is a deal made in February 2014 [5] between Netflix (video-rental company) and Comcast (U.S. network operator). According to the deal, Netflix would pay to the network operator in order to support the development and proper network access for its clients (while the network operator would not financially afford the necessary network investments required by the users specifically for running the new service/Netflix);

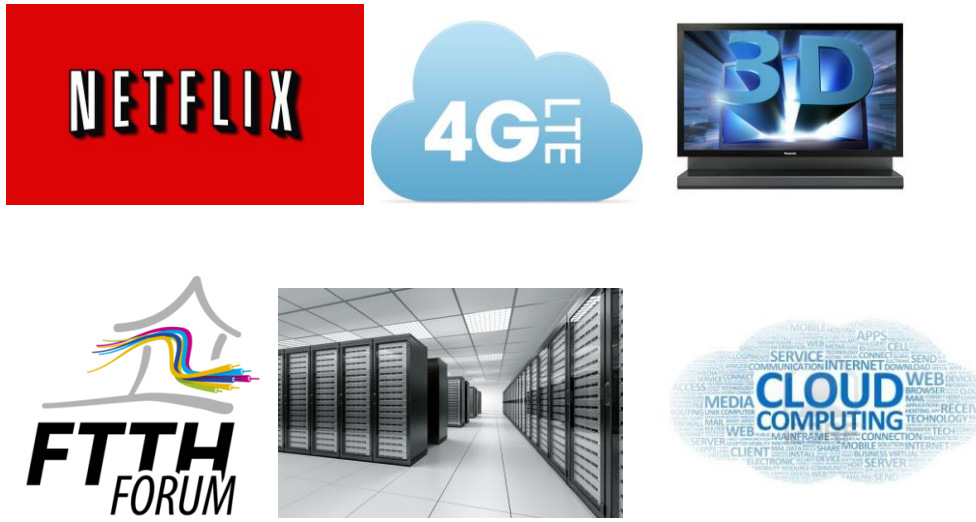


Figure 6. Novel access network technologies and applications driving traffic increase

The Service Level Agreements (SLAs) represent another stress factor on designing and operating core optical networks today. Considering the fact that a network operator can now provide services for many different types of customers, the SLAs become very diverse and introduced tighter constraints for the operators. This faces often the very static nature of the optical resources deployment and determines significant financial investment in order to cope with the requirements. As an example, a financial customer could ask and pay for network connectivity with very low latency and dedicated protection, which could only be provided with transparent optical links. To provide such a link (and in case, provide protection mechanisms too) – depending on the scenario, strong constraints are placed on the network planning and on the operations which would significantly influence the cost.

The energy consumption or the electricity demand is another issue of the core networks and of the ICT industry in general. In a study presented in [6] and emphasized in Figure 7, it can be seen that if the electricity demand would follow a growth proportional with the traffic increase, in less than 10 years a bottleneck can be foreseen due to the limitation given by the maximum amount of produced electricity in the world. However, if the advances in the Silica technology are taken into account,

significant reductions in the electricity consumption can be achieved (blue line in Figure 7). However, the ICT target for the growth in electricity consumption calls for a lower increase and this demands for continuous research and work to be done in the area of energy efficient communication systems.

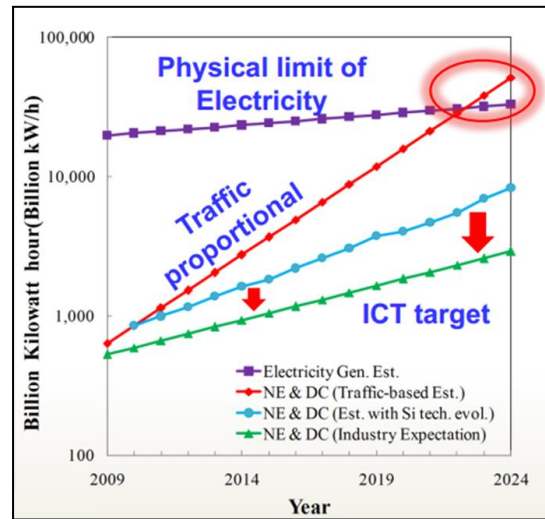


Figure 7. Electricity demand in ICT industry and physical limitation of electricity production [7]

The traffic in core networks experiences various changes from the perspective of the requested connections. This is because the new services are completely different from historical services considering that today there is a significant presence in the network of data-center connectivity, high quality streaming services or medical communications infrastructure. The changes address different parameters of a requested connection and they can be categorized as follows and emphasized in Figure 8:

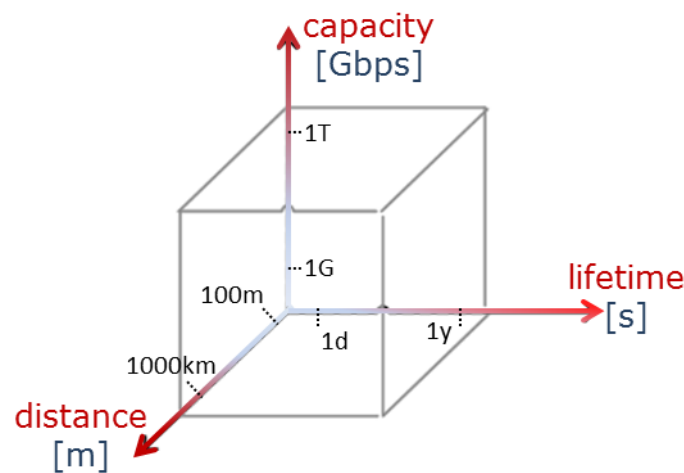


Figure 8. Highly dynamic variation of the optical connection parameters

- Variation in connections' bitrates:
Not long time ago a connection request would have a relatively low variation in terms of bitrate (e.g. STM-1) while lately, with the high increase of the bitrates in parallel with the continuous existence of services which demand a low bitrate – the possible requested bandwidth for a connection can significantly vary. Thus, there can be a data-center request for a back-up operation, which often is described by a high bandwidth requirement (e.g. 100Gb/s). On the other extreme, there can be an isolated mobile base station (BS) which requires an optical connectivity with a relatively low bitrate (e.g. 1Gb/s).
- Variation in connections' lifetime:
An optical connection is not always requested as a permanent link but it can also be defined by a specific lifetime. When taking into account a data-center connectivity backup – such connection can be requested only for a few hours (often during the night). Another example can be that of connecting a temporary TV studio for an event (e.g. Olympic Games) which would only be in place for a few days or weeks. In the other case, when connecting a mobile base station – it is often the case that it is semi-permanently established.
- Variation of connections' distance:
The distance is an important parameter of an optical connection because it is the main factor driving the power budget, regeneration needs, interconnections and other configurations required to set-up the link. When connecting a mobile TV studio (e.g. broadcasting a football game or a concert) – it is normally a matter of kilometers in order to link the stadium or the concert hall with the television's headquarters. On the other side, when a pan-European link connecting facilities of customers placed in different countries can often reach distances of a few thousands of kilometers.

3.3. NORDUnet optical transport network

NORDUnet A/S is a collaboration between the five Nordic Europe countries while it provides interconnectivity between the corresponding five National Research and Education Networks (NRENs): DeIC in Denmark, RHnet in Iceland, UNINETT in Norway, SUNET in Sweden and Funet in Finland. NORDUnet serves the entire Nordic region consisting of five countries and three autonomous areas with a total population of 25 million people using 9 official languages. Together, the Nordic region places as the world's 7th largest economy.

The business value of NORDUnet is to provide a world-class network infrastructure and related services for the nordic Research and Education (R&E) Community which consists of more than 400 research and education institutions and more than 1.2 million users [8].

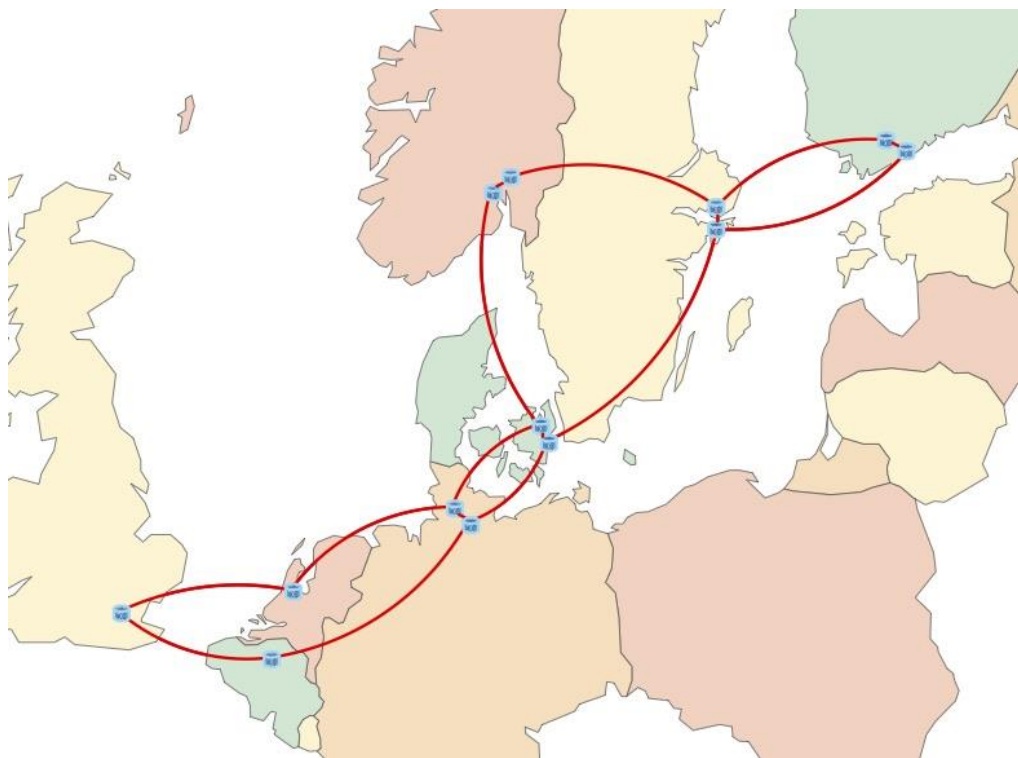


Figure 9. NORDUnet Optical Transport Network [8]

As shown in Figure 9, NORDUnet has its own optical transport network which consists of 4 interconnected ring networks running with 100G lambdas and 10G OTN protected circuit services based on Ciena 6500 Optical Platform.

3.3.1 The NORDUnet transmission network

Optical network architecture in NORDUnet is traditionally based on specialized international high-performance communication systems. The first optical network deployed was built on channel multiplexing, band multiplexing and wavelength blockers, delivered on the 1626 LM (Light Manager) product by Alcatel-Lucent (ALU) and dark fiber from various vendors. This, however, was an interim solution, which at a later stage was to be replaced with wavelength selective switch components (WSS) and tunable transponders. At the time of the network deployment, the WSS components from ALU were considered bleeding edge and state of the art in terms of design, dynamics and flexibility, and it enabled NORDUnet to easily operate 10Gb/s and 40Gb/s client signals in any of the channels in the C-band.

The wavelength selective switching components in the 1626 LM product were utilizing diffraction grating and 2D MEMs (Micro-Electro-Mechanical systems) technology and made multi-degree tunable, reconfigurable optical services and photonic switching possible.

The NORDUnet network topology is a basic ring-type structure with dual presence in each country, as shown in Figure 10, hence providing resilient access to the connected routers (one or more), which are present in all sites, except HMB1 and HMB2 (i.e. Hamburg nodes).

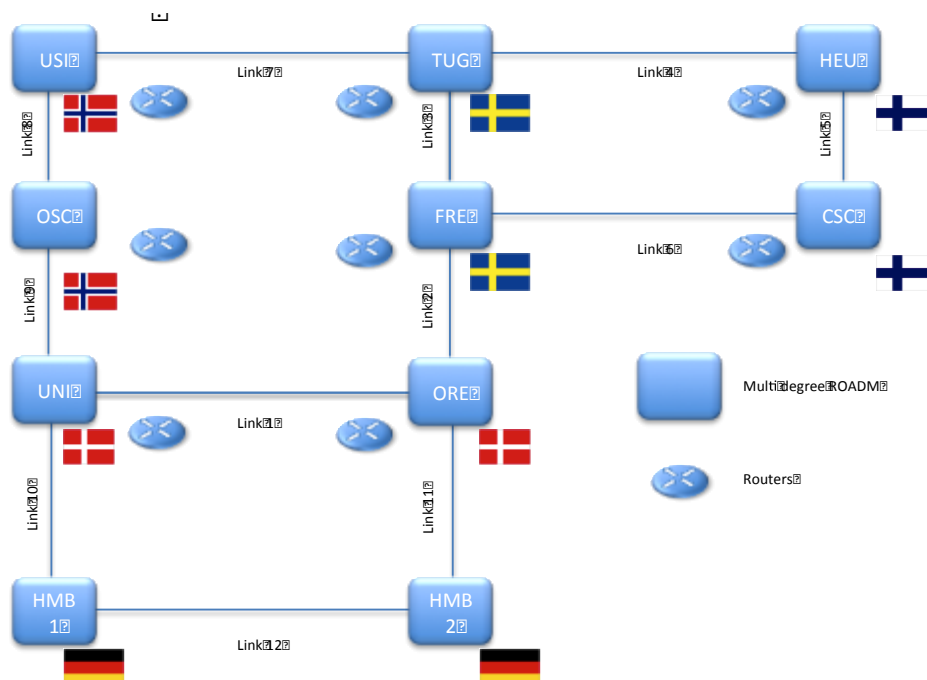


Figure 10. The NORDUnet transmission network

After an obligatory procurement process (in the fall of 2013), NORDUnet kicked off the project “PRISM” to completely replace and upgrade the transmission network together with Ciena which was the selected transmission equipment vendor. Based on recent internal network technology studies, it was clear from the beginning that the new network should be based on coherent 100Gb/s-line technology, 10Gb/s and 100Gb/s client rates, and that the services should be restorable as a minimum for the traffic below 100Gb/s. This restoration capability should be done through an active/intelligent control plane.

NORDUnet believes that future transport network services should be delivered on transparent, agnostic, and open platforms as well as being delivered with the best protection restoration and monitoring capabilities to guarantee first class reliable services. For this reason, amongst others, the addition of an OTN (Optical Transport Network) switching layer was also a requirement from the beginning of the project.

Finally, the network topology was expanded to include London and Amsterdam exchange points in the network topology, as depicted in Figure 11. The latter was achieved as an alien wavelength in the spectrum of the Dutch research and education network SurfNET. In reality, this can be seen as a “native” alien wave as Ciena also delivers SurfNETs DWDM platform. Hence, the optical control functions on the two networks are essentially the same and therefore ease the provisioning efforts.

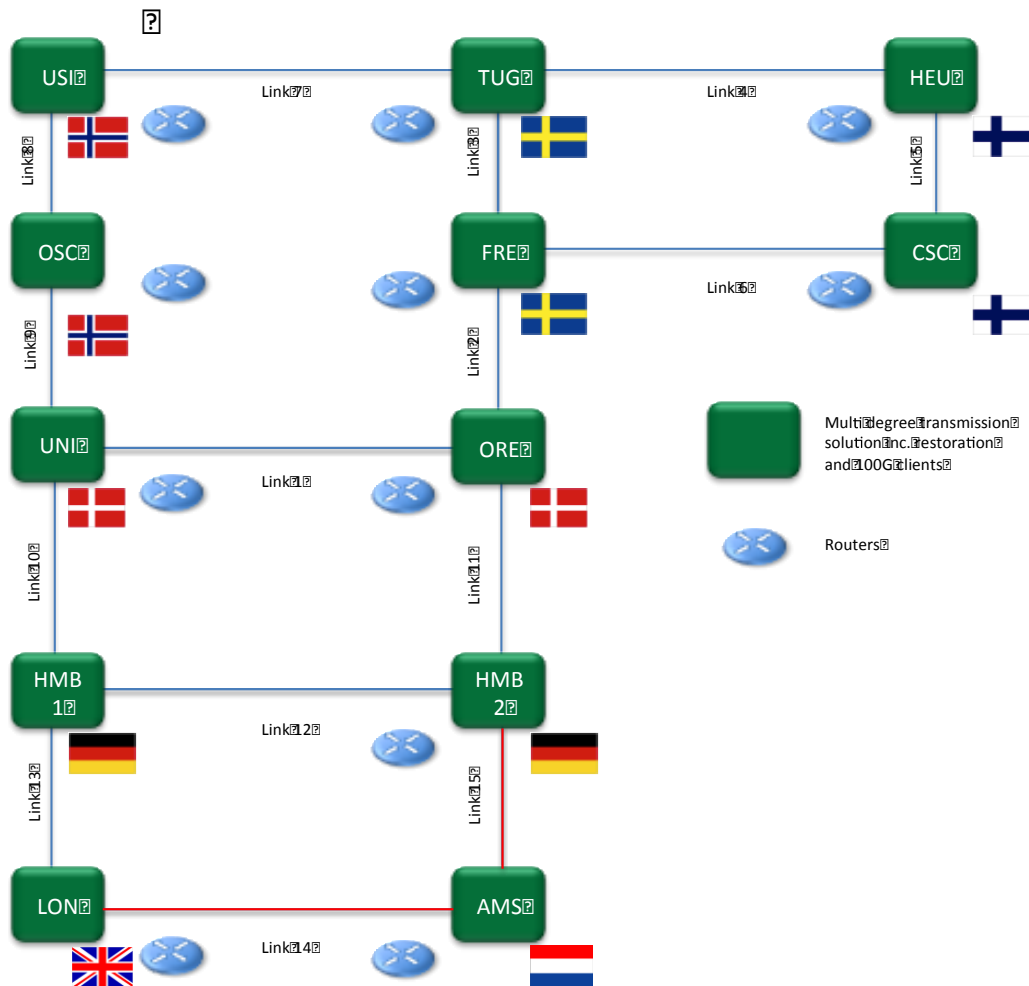


Figure 11. The NORDUnet future network

The selected network architecture was based on Ciena's coherent Wavelength 3 (WL3) technology with advanced modulation and compensation techniques like spectral shaping, PMD (Polarization Mode Dispersion) compensation, and soft decision FEC (Forward Error Correction).

The new optical layer is also WSS-based Reconfigurable Optical Add-Drop Multiplexers (ROADMs) but not tunable anymore as the flexibility has been moved up in the layer 1 with the addition of Ciena's Intelligent OTN Control Plane which provides automated service provisioning and mesh restoration capabilities.

By the end of 2014 the PRISM project was completed and is now operational as NORDUnet's new production transport network.

4. Elastic Optical Networks

Elastic Optical Networks [9] represent a novel network concept, which has been proposed in order to solve major challenges in core optical networks regarding the continuously increasing traffic demand, decreasing revenue per bit, lack of scalability and ever-increasing energy consumption. The introduction of Elastic Optical Networks was facilitated in part by the development of the coherent detection in Wavelength Division Multiplexing (WDM) networks as well as the introduction of the digital signal processing (DSP) modules in the transponders.

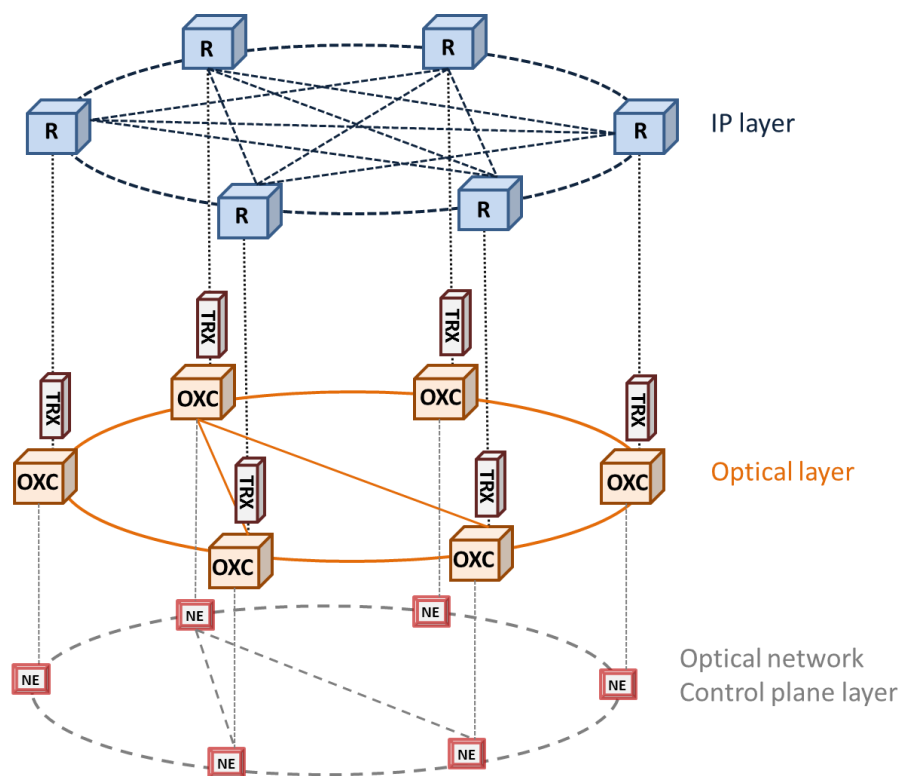


Figure 12. Elastic optical network components

According to the main components of the Elastic Optical Network architecture, depicted in Figure 12, there are four different research directions that have to be addressed:

- ➔ Optical layer: Elastic transponder (TRX) and Elastic Optical Cross Connects (OXC) which have to be capable of handling elastic optical parameters;
- ➔ Electrical layer: Elastic interfaces between Routers and elastic transponders;
- ➔ Management: Control plane in support of elastic connection deployment;

- ➔ Network reconfiguration: New performance predictors and resource allocation algorithms for leveraging the optimized operations;

Elastic Optical Networks consider the variation of multiple parameters, which describe an optical connection with the sole purpose of enabling the flexibility in setting up, or reconfigure that connection in both an offline and online manner. The parameters, which are considered for adaptation, are:

- **Modulation format:**

“Classic” optical networks allow for a fixed or pre-defined modulation format configured on an optical channel – according to the type of the transponders in use. A problem is given by the fact that different transponders with different available modulation formats are needed for serving a 2.5, 10, 40, 100-Gb/s or beyond. Common modulation formats used for 10Gb/s and 40Gb/s connections are RZ/NRZ-OOK (on-off-keying, carrying the information in the amplitude in non-return-to-zero or return-to-zero manner), BPSK, QPSK (Binary/Quadrature Phase Shift Keying, carrying the information in the phase of the optical signal) with or without polarization division multiplexing (PDM) with two orthogonal polarizations. In [10] it is emphasized that for deploying a 100, 200 or 400-Gb/s optical channel at the same symbol-rate (28-32 Gbd), the required modulation formats are PM-QPSK, PM-16QAM and PM-256QAM while enabling 4, 8 and 16 bits/symbol respectively. The consequence of using a more complex modulation format for increasing the bitrate is the exponential reduction of the optical reach and a trade-off is always to be taken into account. One of the reasons of introducing more complex modulation formats was to remain compatible with the 50GHz channel spacing in DWDM networks [13].

- **Symbol-rate:**

The common symbol-rate values for 100Gb/s channels today are 28-32 Gbaud and only slow improvements are expected [11]. However, it is important to enable the reconfiguration of the symbol-rate while keeping a constant modulation format (and a constant optical reach) and achieving different bitrates, (a higher symbol rate allows packing a higher number of symbols into the same time period at the expense of increasing the required channel bandwidth as well as optical signal-to-noise-ratio). Moreover, the symbol-rate variation has its own limitations given by the electronics. When reducing the symbol-rate, the modulation format becomes more and more complex for supporting the same bitrate. However, there are two advantages for lowering the symbol-rate: to use lower speed and cheaper electronic components with lower power consumption as well as reducing the spectrum requirements in order to fit the 50GHz spectrum grid and lower grids (with the adoption of Flex-Grid [10]).

- **Channel spacing:**

DWDM is currently the standard technology to deploy multiple optical channels within a single optical fiber. Recently for coping with the increasing spectral efficiency, narrower channel spacing is taken into account and according to [13], besides the legacy 50 and 100-GHz grid, two narrower ones have been introduced 12.5 and 25-GHz. However, considering that the DWDM system can only select one of the five available channel spacing, it turns out to provide a very inefficient usage (e.g. if 12.5GHz spacing is used, high bitrate channels cannot be accommodated, while if 50GHz spacing is selected and low bitrates channels are used – significant amount of spectrum is wasted). However, in ITU-T's edition 2 from 2012 of defining DWDM spectrum division, the idea of Flex-Grid has been introduced where a channel can have variable spectrum grid assigned. This will be detailed further in Section 4.2.

A review of the impact of Flex-Grid introduction has been made in [12] where it is shown that while lowering the symbol-rate from 28 to 14Gbaud, while changing the modulation format from QPSK to 16-QAM, the required spectrum grid decreases from 50GHz to 25GHz (at the expense of reducing the optical reach from 3500 to 1200 km).

- **Forward Error Correction:**

Forward Error Correction (FEC) modules are an important component of the transponders in order to support an improved Bit Error Rate (BER) and extend the optical reach of the signal [14]. The challenge with today's implementation of FEC modules in transponders is that they are statically configured meaning that whatever the distance of a requested optical channel is, the FEC module works with the same overhead and the same efficiency. Thus – a good approach in support of the elastic optical networks concept is to enable adaptation of the implemented FEC module and be able to select between a set of predefined FEC codes with different efficiencies according to the requested distance, capacity to be transported and channel physical conditions [15].

Once the adaptation is enabled at all the four parameter levels, a much better utilization of the optical resource can be achieved (without exceeding the physical limitations) throughout transponders and optical cross connects. Moreover, the optical resources can indeed be used as an on-demand service while being able to adapt to various customer demand (e.g. they can better adapt to day/night fluctuations by re-tuning the capacity and thus limiting the amount of required overprovisioning).

The elastic interfacing between the client layer (IP/MPLS) and the optical layer (transponder) was addressed in Celtic EO-Net project [16] with a novel approach based on 100GbE. The solution proposed to address the variable 100GbE incoming traffic with 10 lanes of 10Gb/s each and thus send to the transponder a variable bitrate. Moreover – in order to ensure the granularity of the output traffic, there were three solutions proposed: to turn on and off some of the 10Gb/s lanes (hence, ensure a

10Gb/s granularity), to vary the bitrate of each lane (e.g. at a 1Gb/s granularity) or the combination of the two.

Since elastic optical networks change the static paradigm of the optical deployment towards a rather dynamic approach, a significant impact is made on the control functions. A new approach on control plane architecture has to be made in order to cope with the challenges brought by the dynamicity of the parameters. Currently, two approaches have a significant research interest and they refer to extending the current GMPLS standards and a more disruptive approach based on Software Defined Networks (SDN) and partially making use of OpenFlow protocol. Moreover, hybrid approaches are proposed while trying to combine the benefits of the two approaches. More details on the control plane strategies for Elastic Optical Networks are given in Section 5.

4.1. Elastic Optoelectronic Devices

There has been significant work on proposing different elastic transponders designed such as the ones based on single-carrier technologies. In [17] and [18] a format-versatile transceiver and coherent detection schemes derived from 100Gb/s polarization-division-multiplexed quaternary phase shift keying (PDM-QPSK) enable a data-rate tuning from 25 to 100Gb/s with a 25Gb/s step. In [19], eight modulation formats and symbol-rates up to 28Gbaud were used and they could be switched in the nanosecond regime reaching up to 336Gb/s with 64QAM modulation format in a dual polarization setup. Moreover, solutions based on Orthogonal Frequency Division Multiplexing (OFDM) were also proposed: in [20] adaptive OFDM transponders use coherent transmission with polarization multiplexing and results showed that reach dependent capacity improves significantly the network performance. In [21] a novel architecture named “SLICE” proposes a transponder, which takes client data and maps it in G.709 OTN frames, which are then transformed onto the optical OFDM signal (i.e. OFDM enables transmitting the data over multiple orthogonal subcarriers with a frequency spacing of the inverse symbol duration). In [22] the hardware efficiency of the variable bitrate transponders based on OFDM is demonstrated for a bitrate range 10-100Gb/s. Another novel approach was proposed in [23] where an optical transmitter based on dynamic optical arbitrary waveform generation (OAWG) was used to create high bandwidth data waveforms in any modulation format and thus allowing software defined transmission parameters acting as a flexible bandwidth transponder.

The work performed along this Ph.d. project considered the elastic transponder proposed in the Celtic EO-Net project ([2] and [16]) based on single-carrier 100Gb/s PDM-QPSK coherent detection. The transponder considered the variation of the four parameters: modulation format, symbol-rate, channel spacing, and forward error correction (FEC) as it follows:

- ➔ The elastic transponder, presented in [24], is able to tune between different modulation formats. Single polarization binary phase shift keying (SP-BPSK) is achieved when having identical independent binary signals ($I1=Q1=I2=Q2$) and thus obtaining 1 bit per symbol which enables a 25Gb/s payload. Polarization division multiplexed – binary phase shift keying (PDM-QPSK) is implemented when the two pairs of binary signals are equal ($I1=Q1$ and $I2=Q2$) achieving 50Gb/s. Polarization-switched QPSK (PS-QPSK) encoded with $Q1 = I1 \text{ XOR } Q1 \text{ XOR } I2$ allowing 75Gb/s payload. Moreover, the PDM-QPSK encoding with four different binary signals $I1$, $Q1$, $I2$, and $Q2$ achieve 100Gb/s. The data-rate vs. reach tradeoff for these modulation formats is detailed in Table 1. It is important to note that they are reach dependent and according to the studies made in [24] show that the power consumption of the format-adaptive transponder does not depend on the chosen modulation format

and it is similar to the power associated to a standard 100Gb/s PDM-QPSK transponder.

Format name	SP-BPSK	PDM-QPSK	PS-QPSK	PDM-QPSK
Data rate at symbol rate R	1R	2R	3R	4R
Distance L at optimum power	3L	2L	1.5L	L

Table 1. 100Gb/s PDM-QPSK available modulation format configuration [16]

- ➔ The symbol-rate can be switched between 7, 14, 21 and 28-Gbaud while keeping the same architecture of the 100Gb/s single-rate transponder and only tuning the clock reference. The work done in [24] shows that when tuning the symbol-rate the optical reach remains approximatively the same. However, considering that in coherent receivers a large part of the power consumption is generated by the data processing of the ASICs and/or FPGAs (framer, FEC codes and DSP blocks), the power consumption of the transponder can be approximated in a linear relation with the clock frequency. Hence, four different power consumptions were obtained: 189, 206, 255, and 350 W for the four different symbol-rates associated to 25, 50, 75 and 100Gb/s data-rate configuration.
- ➔ The 100Gb/s PDM-QPSK elastic transponder does not consider specific spectrum grid tuning but constraints can be considered in order to generate certain spectrum-slice characteristics. More details on channel spacing are in Chapter 4.2.
- ➔ The FEC code adaptation is taken into account at the FEC modules for the coding and decoding procedures when varying the overhead (due to the data-rate variation) as shown in [25] where variable-rate FEC codes were used with variable signal constellations and a fixed symbol-rate. Also, an important aspect related to the elasticity of the FEC codes refers to the possibility of reducing the energy as shown in [26] where a Low Density Parity Check – based (LDPC) encoding was used and a pre-determined minimal number of iterations could be made at the receiver stage by having an estimate model for the bit-error-rate (BER). Moreover, in [27] an adaptive forward error correction (FEC) allows to perform continuous adjustments to its own code rate by adding extra parity bits to the data stream when extra capacity is available. The results show that the additional parity information can decrease the number of necessary decoding iterations, which in turn reduces the power consumption in iterative decoders when the data-rate variations experience low peaks.

In addition, it is important to consider that Optical Cross Connects (OXC) and Wavelength Selective Switches (WSS) are also required to work with variable optical filtering and allow bandwidth variable channels operation. Enabling OXC and optical filters (like WSSs) to handle bandwidth variable spectrum has been made by the introduction of Bandwidth Variable - Wavelength Selective Switches (BV-WSS) based on Liquid Crystal on Silicon (LCOS) and micro electro mechanical systems (MEMS) technologies as described in [28] and [29].

4.2. Flexible grid

The optical transmission systems were able to reach impressive advances regarding the total available capacity within an optical fiber without facing the physical limitation of the capacity given by the available optical spectrum in a fiber. Once the new 100Gb/s systems were introduced at a large scale, a typical 50GHz grid was completely filled with one channel at 2 bits/Hz spectral efficiency. Moreover, new technologies such as 200Gb/s, 400Gb/s or even 1Tbps would require a 75, 100 or even 200GHz spectrum. Hence, it can be foreseen that in an optical system where connections would vary in bandwidth between 10 or 40GHz up to 1 THz, spectrum spacing with significant variations has to be accommodated and thus it needs to be provided in a more flexible way.

Flex-Grid considers a lower channel spacing (25, 12.5 and 6.25GHz, according to ITU-T's specifications in [13]) and the possibility of using more contiguous spectrum slots for one single optical channel (see Figure 13). The lower limit of 6.25GHz defined by ITU-T was chosen while taking into account the physical limitations as well as the increasing cost of the optical filters and bandwidth variable wavelength selective switches (BV-WSSs). Hence, by reducing the grid, a significant gain is given at the cost of increased complexity of the optical filters, which have to handle small spectrum slots. In [30] a stress-case study of Flex-Grid was performed where the spacing was narrowed down to a “gridless” context and the results showed that at a certain granularity (i.e. 3GHz) the achieved performance is similar to the one of “gridless” case. Moreover, the problem of spectrum spacing reduction is more complex considering also the filtering-induced impairments. The work in [31] shows that a 37.5GHz channel spacing can ideally enable 33% extra available spectrum when compared to a 50GHz grid; however, when filtering penalty is introduced in the simulations the results show that in transparent network scenarios the extra available spectrum is drastically reduced.

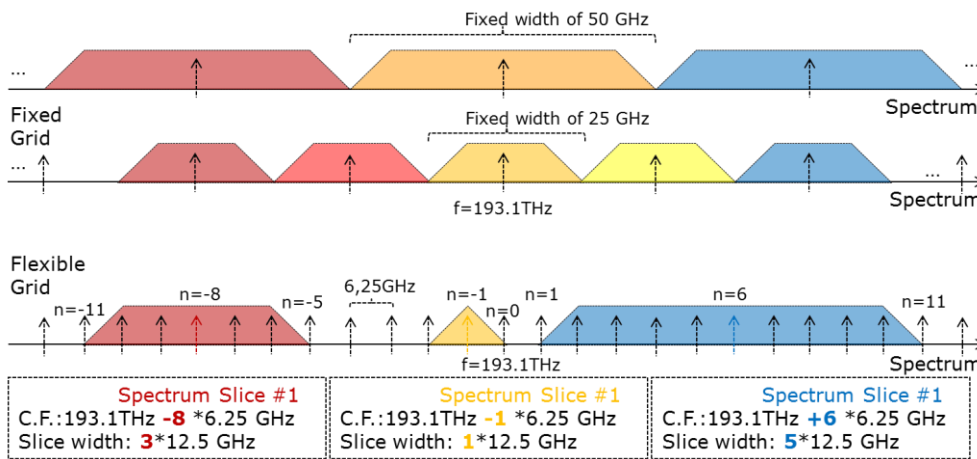


Figure 13. Flex-Grid architecture and slice definition

Figure 13 shows a comparison between two Fixed-Grid deployments (50GHz and 25GHz) and a Flex-Grid architecture. It can be observed that in Fixed-Grid the channel spacing is rigid and it cannot be tuned to a certain request of spectrum width. However, the Flex-Grid concept introduces the idea of a slice, which consists of a number of contiguous Elementary Spectrum Slots (ESSs). The ESS is referred as the smallest defined channel spacing (e.g. 6.25 in Figure 13) which cannot be further divided. Hence, an optical channel can be assigned to a spectrum slice with a variable size depending on the number of contiguous ESS that it contains.

There are a number of parameters, which define a Flex-Grid system as proposed in [32] and [33]:

- Frequency slot (or spectrum slice) – referred as a frequency range allocated to (or reserved for) a given channel; in the work presented in this thesis, this is referred as a “slice” consisting of multiple contiguous elementary spectrum slots (ESS);
- Spectral slice (or Central Frequency Granularity/CFG) – represents the spacing between allowed central frequencies (e.g. 6.52GHz)
- Slot width (or Spectrum Slice Width/SSW) – represents the complete width of a frequency slot/slice in the flexible grid;
- Slot width granularity (or Spectrum Slice Granularity/SSG) – defines the step that provides possible values for the width of a Spectrum Slice (e.g. for ITU-T’s recommended 12.5 Spectrum Slice Granularity/SSG, a slice width can be: 12.5, 25, 37.5 etc.)

In Figure 13 three slices are described with different widths and it can be observed that Spectrum Slice #1 consists of 6 ESSs while spectrum slice #2 consists of 2 ESSs. Moreover, from a control point of view, every spectrum slice is described based on two elements, as proposed in [33]:

- Nominal central frequency (f): denoted as “n” and can be always built by following the formula:

$$f = 193.1 \text{ THz} + n \times 0.00625 \text{ THz} \quad \text{eq. (1)}$$

“f” is integer positive, negative or 0;

193.1 THz is ITUT’s central frequency for transmission over C band;

- Slot width (or slice width): denoted as “m” and it is given by the following expression:

$$\text{Slice width} = m \times \text{SSG} \quad \text{eq. (2)}$$

SSG represents the Spectrum Slice Granularity;

“m” is integer greater or equal to 1;

In Figure 13, it can also be observed that Spectrum Slice #1 is defined by a nominal central frequency equal “-8” and a slice width equal “3”; while Spectrum Slice #2 is defined by $n=+6$ and $m=+5$;

There are different challenges, which Flex-Grid architectures are facing, and apart from the associated control plane implementation, which will be detailed in the following sections, fragmentation represents one of the main issues that have to be addressed. Fragmentation represents the case when due to a high dynamicity of connection requests, different spectrum slots are reserved along the available spectrum in a fiber causing multiple available slices, each of them having a spectrum width smaller than the common connection requests. Hence, despite the fact of having overall significant amount of available spectrum, it is impossible to find a contiguous set of spectrum slots in order to fulfill the minimum spectrum requirements given by a connection request.

The classical solution to reduce the spectrum fragmentation in optical links is to use the control plane for re-allocating the connections in a way, which minimizes the fragmentation. Two common methods for performing spectrum slots reallocation are Make-Before-Break [34], which is a possibly disruptive method, and a hitless method, which takes into account to re-assign a channel in neighboring positions over the same link in the path while avoiding channel losses.

The Make-Before-Break method is not recommended for dynamic network scenarios because it takes into account changing the existing path for the connection that is to be re-allocated in spectrum. Thus, when performing the transition from the existing route to the new one, despite the existence of buffer memories it is likely to experience traffic loss.

In the case of hitless de-fragmentation methods, commonly push-pull [35] techniques is used in order to re-allocate the existing spectrum slots to a neighboring position in such a way that the merged spectrum of the current slice and of the newly selected slice will form a single contiguous spectrum slice. In this way, the generated laser spectrum width can re-tune from the initial slice to the merged spectrum slice while shifting the central frequency. Afterwards, the central frequency is shifted once again and the spectrum slice is reduced in order to position the laser on the final spectrum position. The advantage of this method is that the traffic perceives the re-configuration in a transparent way and thus it is non-disruptive. Previous work [35], [36] and [37] have proposed hitless de-fragmentation techniques while [37] is using OSPF-TE routing information in order to obtain spectrum information on all links and then use it for re-allocation decisions.

5. Control planes for Elastic Optical Networks

5.1. Distributed control plane

One of the most common solutions proposed to control Elastic Optical Networks and Flex-Grid architectures was a GMPLS [38] based control plane. A reason for choosing GMPLS to enable management and control in an elastic optical network was the fact that GMPLS is today a mature control framework, which is already adopted by more and more operators while extending the capabilities of GMPLS can be done relatively easily following the ongoing standardization process.

GMPLS consists of three main functions, which can be provided with different protocol choices. The link discovery management protocol is commonly provided using LMP [39] protocol. The routing function can be realized with Open Shortest Path First – Traffic Engineering (OSPF-TE) [40], [41] or Intermediate System to Intermediate System (IS-IS) [42] protocol. Signaling function can be provided with Resource ReserVation Protocol – Traffic Engineering (RSVP-TE) [43] or Constraint-based Routing Label Distribution Protocol (CR-LDP) [44]; however, from 2003, IETF MPLS working group decided to mainly focus on RSVP-TE for signaling in MPLS/GMPLS networks [45].

The Link Management Protocol (LMP) is responsible to manage Traffic Engineering resources and link attributes within GMPLS. Considering that in large networks, managing the attributes of the physical resources in a manual way is not scalable, LMP is proposed to provide an automatic process for managing traffic-engineering links. As described in [39], the main two functions of LMP are to provide control channel management and traffic engineering link property correlation while LMP could also provide physical connectivity verification and fault management. From an elastic optical network applicability point of view, LMP is required to be able to manage link properties that can change while enabling elasticity such as spectrum grid properties (central frequencies spacing, minimum and maximum width, etc.).

5.1.1 Routing and Open Shortest Path – Traffic Engineering (OSPF-TE)

OSPF-TE is responsible within GMPLS protocol suite for performing the routing procedure. As described in [41] and also emphasized in Figure 14, the properties of the GMPLS TE links are advertised using specific packets called Link State Advertisements (LSAs). The TE LSAs are advertised by every node to the other

nodes in the network so that after the flooding has converged, every node can have the overall picture of the available resources in the whole network area.

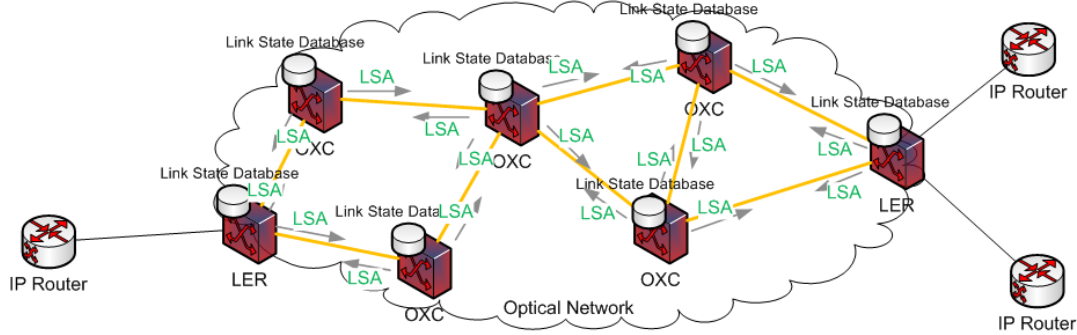


Figure 14. OSPF-TE advertisements in GMPLS control plane

The TE LSAs are opaque LSAs with an area flooding scope and they have only one top-level TLV (Type Length Value) triplet [40] and one or more sub-TLVs which can be used for extensions. These sub-TLVs are also targeted in elastic optical networks for being used as extensions to advertise elastic parameters. At the end of the flooding process, each node can gather the resource availability information in a database. Path Computation algorithms can then use this database in order to select a certain path with corresponding resources according to the incoming request. Figure 14 emphasizes the presence of a database in every GMPLS node where information about Flex-Grid resources is gathered together with information about elastic parameters or other information, which can be required by the Path Computation algorithm.

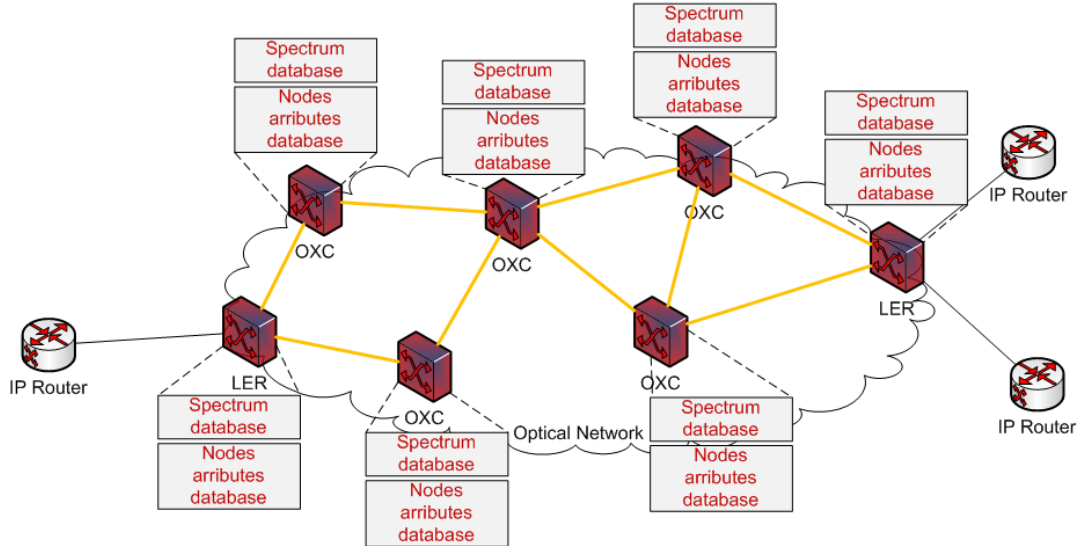


Figure 15. Advertising Flex-Grid information via OSPF-TE

Figure 16 shows the encapsulation format of a Traffic Engineering (TE) Link Local LSA [41], which is used to advertise traffic engineering information over a given interface to the neighbors connected to that interface. Hence, as shown in Figure 16, a TE Link Local LSA is a so-called opaque LSA with type 9 (acting as link-local flooding) while Opaque Type is 1 (equivalent to TE LSA). The information is then encapsulated in the TE LSAs.

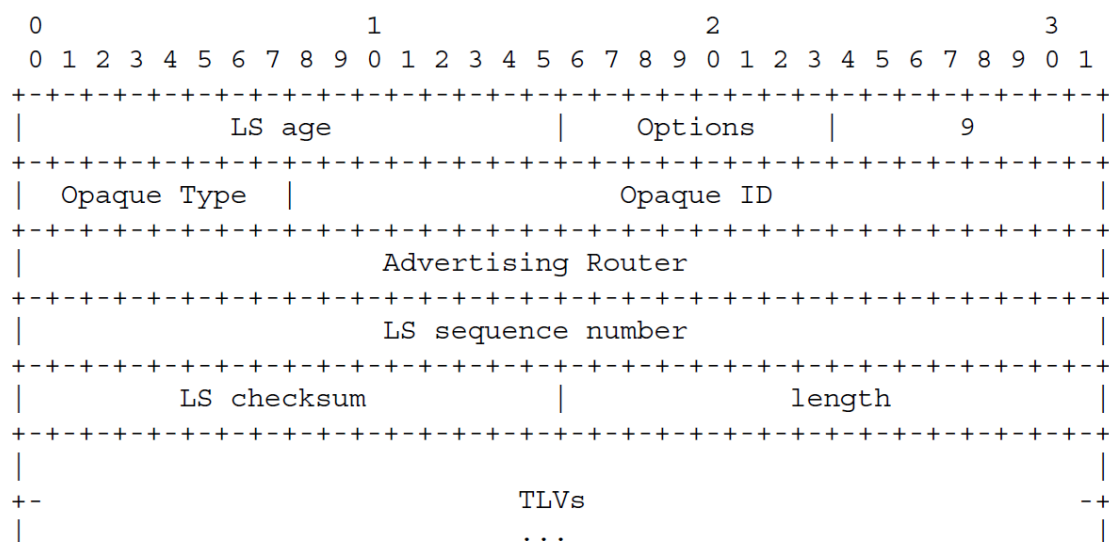


Figure 16. A Traffic Engineering Link Local LSA format

Concerning elastic optical networks, OSPF-TE has to be able mainly to handle flexible spectrum operations. Hence, apart from the wavelength switching capability, in [46] the new Spectrum-Switch-Capable (SSC) switching capability is introduced and gets assigned value “102”. Moreover, two formats to advertise spectrum slots information are proposed:

- ➔ Bit-Map format (type 1 sub-TLV): each bit in the Value field of the sub-TLV represents the availability of one spectrum slot of width equal to the value in SS field (Spectrum Slot spacing: 1, 2, 3 or 4 for 100, 50, 25 and 12.5-GHz respectively);
- ➔ List and Range format (type 2 sub-TLV): there are more entries in the Value field which contain two values – a Start and an End Spectrum Slot identifier which define a part of the spectrum advertised as busy/used;

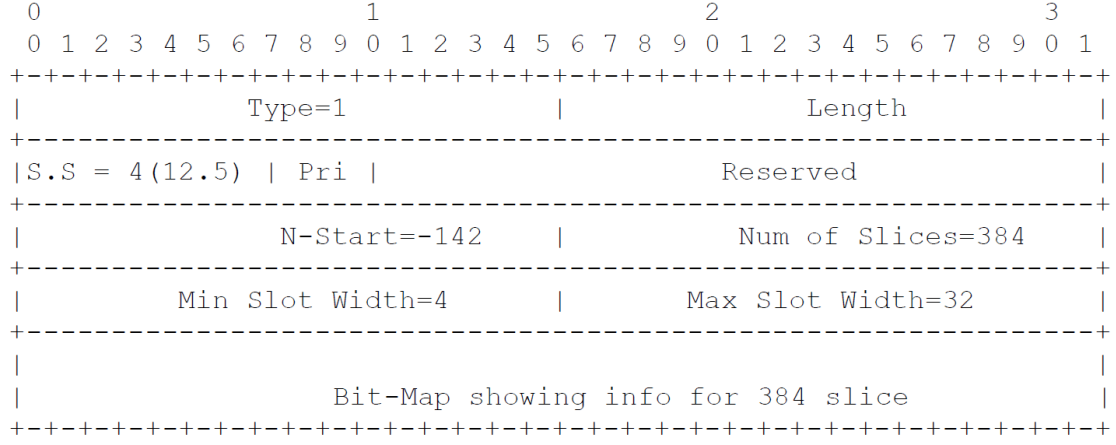


Figure 17. Type 1 sub-TLV showing a Bit Map format encoding of Flex-Grid information within OSPF-TE LSAs

Figure 17 shows the encoding of a TE LSA, which advertises the availability of the spectrum slots within a link. It is important to note the type (which reflects the Bit-map encoding in the Value field) and the Slice/Spectrum Spacing (SS) value of “4” (representing a 12.5GHz spacing) while the “N-start” value of “-142” identifies the usage of an extended C-band spectrum and the presence of “384” slices/spectrum slots (separated by 12.5GHz, resulting into 4.8 THz available spectrum). The “Min/Max Slot Width” determines the fact that an LSP can request a spectrum slice with a minimum width of 50GHz (4x 12.5GHz) and a maximum width of 400GHz (32 x 12.5GHz). The last part of the Value field enlists 48 bytes, which give the status of every slice/spectrum slot out of the total 384.

Initial work [47] and [48] on performing routing and using OSPF-TE for handling elastic optical network connections focused on using a simplified encoding for flooding physical layer information using TE LSAs. Thus, the dynamic status of the frequency slots was not advertised but instead OSPF-TE extensions were used to advertise information about aggregated bandwidth for each link. This was a preferred choice both because IETF hasn’t had standardized yet the encoding for advertising spectrum slots statuses and also it implies having a simplified OSPF-TE control plane operation. Also, work in [49] and [50] emphasized the fact that the dissemination of the available frequency ranges associated to the spectrum slots by using OSPF-TE is to be further investigated since it raises challenges concerning scalability due to the high number of nominal frequencies in the C band when using small channel spacing.

The IETF draft [51], which defined the Routing and Wavelength Assignment (RWA) information for Wavelength Switched Optical Networks (WSONs), has been extended by the work in [49]. There, a new Explicit Route (ERO) sub-object was defined in order to allow the elastic parameters (i.e. modulation format, FEC, spectrum) to be carried as TLVs either within RSVP-TE signaling or by PCEP (Path Computation Element Protocol) [52].

5.1.2 Resource ReserVation Protocol – Traffic Engineering (RSVP-TE)

RSVP-TE is responsible for signaling in GMPLS controlled optical networks; thus, RSVP-TE handles the configuration of all cross-connects which are supporting the optical connection by using a message exchange from the ingress Label Edge Router (LER) to the egress LER, as emphasized in Figure 18. Hence, a PATH message is used to announce the attributes of the newly requested LSP and from the egress node a RESV message returns to trigger the actual reservations.

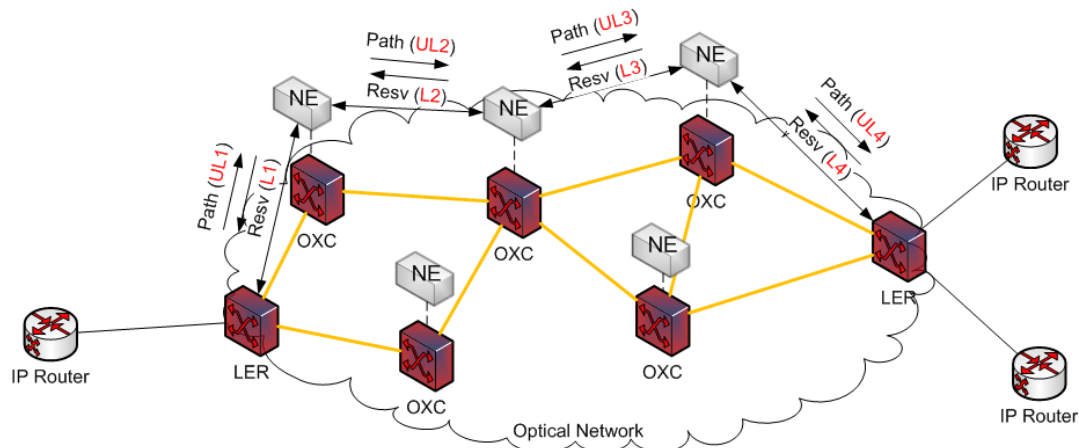


Figure 18. RSVP-TE signaling in GMPLS control plane

RSVP-TE is commonly used today to reserve a wavelength for an optical channel and this functionality has to be extended in order to enable the set-up of elastic optical connections. Three main directions need to be addressed for extending RSVP-TE towards elastic capabilities:

- ➔ Path message has to transport a parameter, which defines the amount of spectrum that is required to be reserved. Compared to the case of Fixed-Grid networks, an LSP can differ from the point of view of the amount of specified spectrum. Hence, a new parameter entitled “m” in [53] was proposed and previously described in Section 4.2. Two objects are going to describe the Flex-Grid attributes in PATH and RESV messages [53]:
 - In PATH message: the *SENDER_TSPEC* object which indicates the requested resource reservation (bandwidth/label/spectrum request); *SENDER_TSPEC* Class 12 is assigned for Flex-Grid networks;
 - In RESV message: the *FLOWSPEC* object which indicated the actual resource reservation (bandwidth/label/spectrum confirmation); *FLOWSPEC* Class 9 is assigned for Flex-Grid networks;

- ➔ The definition and encoding of the new labels (slices/spectrum slots) has been defined in [54]. The label concept (as known from Fixed-Grid networks) has to be generalized and a new format has to be used in order to enable the description of both fixed-grid and Flex-Grid LSPs. For compatibility reasons, the generalized label format is modeled on the fixed grid label defined in [55] as described in Figure 19:

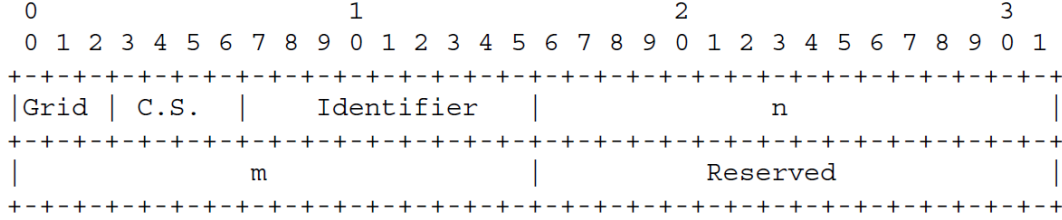


Figure 19. The Flex-Grid label encoding

Thus, the new generalized label concept introduces new values for “Grid” and “Channel spacing (CS)” parameters as shown in Table 2:

Grid	Value	CS	Value
Reserved	0	100GHz	1
ITU-T DWDM	1	50GHz	2
ITU-T DWDM	2	25GHz	3
ITU-T Flex	3	12.5GHz	4
Future Use	4-7	Flexible Grid	5
		Reserved	Other

Table 2. Grid and channel spacing values in a Flex-Grid architecture

A Flex-Grid environment introduced the new Grid type “ITU-T Flex” and assigned one of the previously reserved values (i.e. 3) while the channel spacing considers a new value (i.e. 5) as indicating a Flex-Grid enabled network. Moreover, while in Fixed-Grid networks the CS value represented the channel spacing as being the spacing between two adjacent channels (and always a constant value), in Flex-Grid networks, the CS field describes the nominal central frequency granularity.

The “Identifier” and “n” fields from the generalized label (Figure 19) remain unchanged from the Fixed-Grid labels definition [55]. In addition, the newly introduced field “m” is defined according to the descriptions in Chapter 4.2. It is important to note also that RSVP-TE signaling is a distributed approach and the generalized lambda interpretation has to be possible at each hop along the path.

5.1.3 Routing Modulation and Spectrum Assignment (RMSA)

In Wavelength Switched Optical Networks (WSONs) the problem of finding a physical route (routing) and allocating a wavelength (or label) is known as Routing and Wavelength Assignment (RWA). In Spectrum Switched Optical Networks (SSONs) the equivalent process is referred as Routing, Modulation and Spectrum assignment (RMSA). An RMSA process is responsible to compute:

- ➔ A physical route from source to destination;
- ➔ A set of contiguous spectrum slots available on all links along the path (also called Spectrum Continuity Constraint / SCC);
- ➔ A set of elastic parameters such as: modulation format, number of OFDM sub-carriers, Forward Error Correction (FEC) code, etc.;

As described in [33], there are multiple architectural approaches for the RMSA process:

- Combined RMSA (Routing & MSA): represents the case when a single entity computes with a dedicated algorithm at the same time both the routing and the spectrum slots assignment. This case requires that the respective entity (e.g. PCE element or Ingress node) has the overall network resource and connectivity information (i.e. spectrum availabilities, links, interfaces, etc.);
- Separated RSA (Routing + MSA): represents the case when one entity handles the routing path while another entity handles the modulation and spectrum assignment problem. This requires that each entity has the required information (first entity requires the link connectivity information and eventually overall resource availability information for performing advanced routing decisions; the second entity only requires resource availability information in the network);
- Routing and Distributed MSA (Routing + DMSA): represents the case when one entity handles the routing decision while the modulation and spectrum assignment are handled in a distributed manner by collecting hop-by-hop the availability of the resources (modulation formats, spectrum slots, etc.) and taking a decision at the egress node between the commonly available resources along the path (often GMPLS and RSVP-TE is used for collecting the available resources and reserving them);

Figure 20 provides an example of Combined or Separated RMSA where the Modulation and Spectrum are chosen before the signaling procedure is initiated with RSVP-TE PATH message. Hence, in current example, an LSP with a spectrum slice width “m”=2 is requested and based on the overall resource information available in Node A, it is decided that central frequency “n”=2 is to be used. RSVP-TE PATH message goes from source to destination checking (once again) the availability of the

slice and if no changes occur, a RESV message returns from egress node to ingress node reserving the spectrum slice along the path.

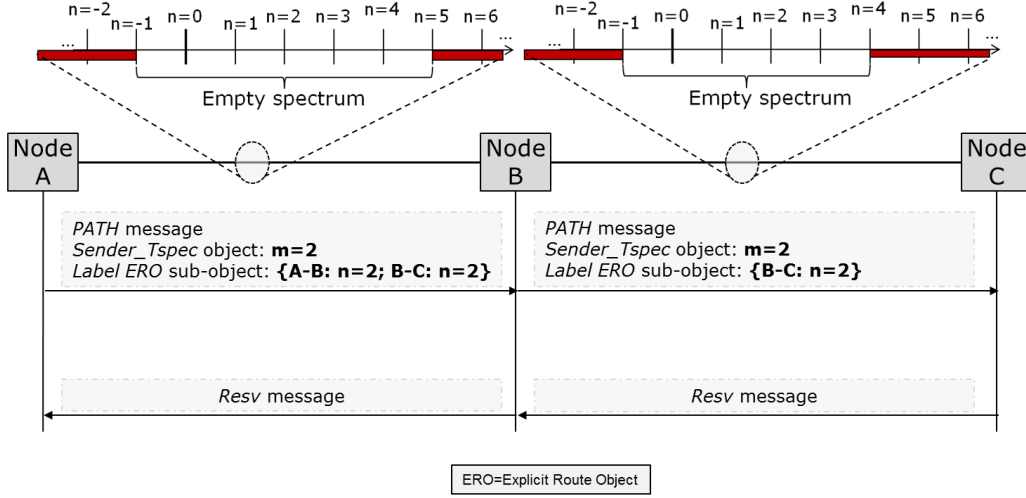


Figure 20. Centralized spectrum assignment

Figure 21 provides an example of Routing and Distributed RMSA where Node A is (eventually) not aware of the available resources in the network and thus it only performs the routing procedure and chooses a path (A-B-C). Afterwards, an RSVP-TE procedure is initiated with an input of spectrum slice width requirement of “ m ”=2. A PATH message checks the availability of the spectrum slots from the ingress node to the egress node and collects the commonly available central frequencies which are available for a slice width of “ m ”=2. When the PATH message reaches the egress node (Node C), a local policy decision (e.g. First Fit, Random Fit, Last Fit, etc.) chooses one of the available central frequencies and returns a RESV message to the ingress node which makes the reservation of the spectrum slots assigned to the chosen slice.

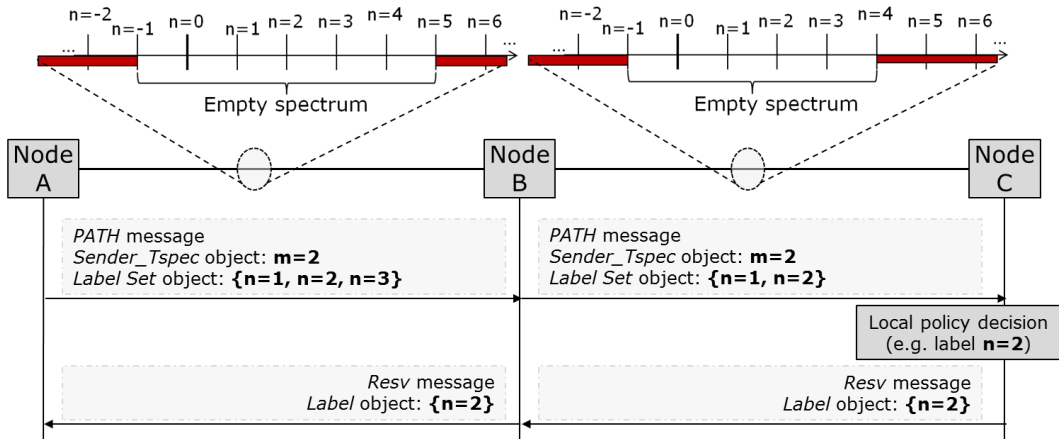


Figure 21. Distributed Spectrum Assignment

Multiple studies addressed the issue of offline RMSA planning [56] - [61] while others focused on the online dynamic RMSA problem [62]-[71]. In the work performed within this thesis, the focus is on dynamic RMSA approaches only.

5.2. Software Defined Networks and centralized control plane architecture

The software defined optical transport networks is not included in the research objectives of this thesis but in order to have an overall view of the state-of-the-art in optical transport networks it is important to mention also the competing technologies.

The focus on centralized control plane solutions in optical transport networks started to raise once the Software-Defined Networking (SDN) concept became a main research-topic in the last years. The idea of having software-defined network functions is not a novel concept in the area of telecommunications but the introduction of OpenFlow (OF) [72] in support of SDN architecture represents a novel approach. OF and associated architectures based on SDN and OF received a higher interest due to the continuous industry support in developing OF within Open Networking Foundation (ONF) organization [73]. SDN architecture differs from traditional networking due to its ability to separate the control plane from the forwarding plane while supporting the architecture of software-defined networks acting as southbound application programming interface (API) (as shown in Figure 22). SDN allows programming the network infrastructure based on the idea of decoupling applications (or network services) from the physical infrastructure. Hence, using OF (or any other solution for southbound API, e.g. sFlow) a layer of abstraction from the physical network to the control element is provided and this allows the network to be configured and controlled through software code while opening up a huge opportunity for providing innovation.

As depicted in Figure 22, the SDN architecture considers the separation of data-plane, which becomes a simple forwarding hardware and the control plane at the physical layer consisting of an OpenFlow agent, which has to ensure communication with the centralized network control. Moreover, SDN architecture consists of three main components or functions:

- an open vendor independent interface (preferably; but it can also be a vendor specific interface) where the most popular and industry supported solution is OpenFlow; the role of this interface is to work as an API between the physical nodes and the centralized operating system;
- the Network Operating System (or also referred as SDN controller) consists of a centralized environment for running the network functions;
- open APIs represent the northbound APIs which enable 3rd party service development on top of the provided network infrastructure; in this case service providers are able to benefit from the fact that there are no more compatibility restrictions related to the physical infrastructure;

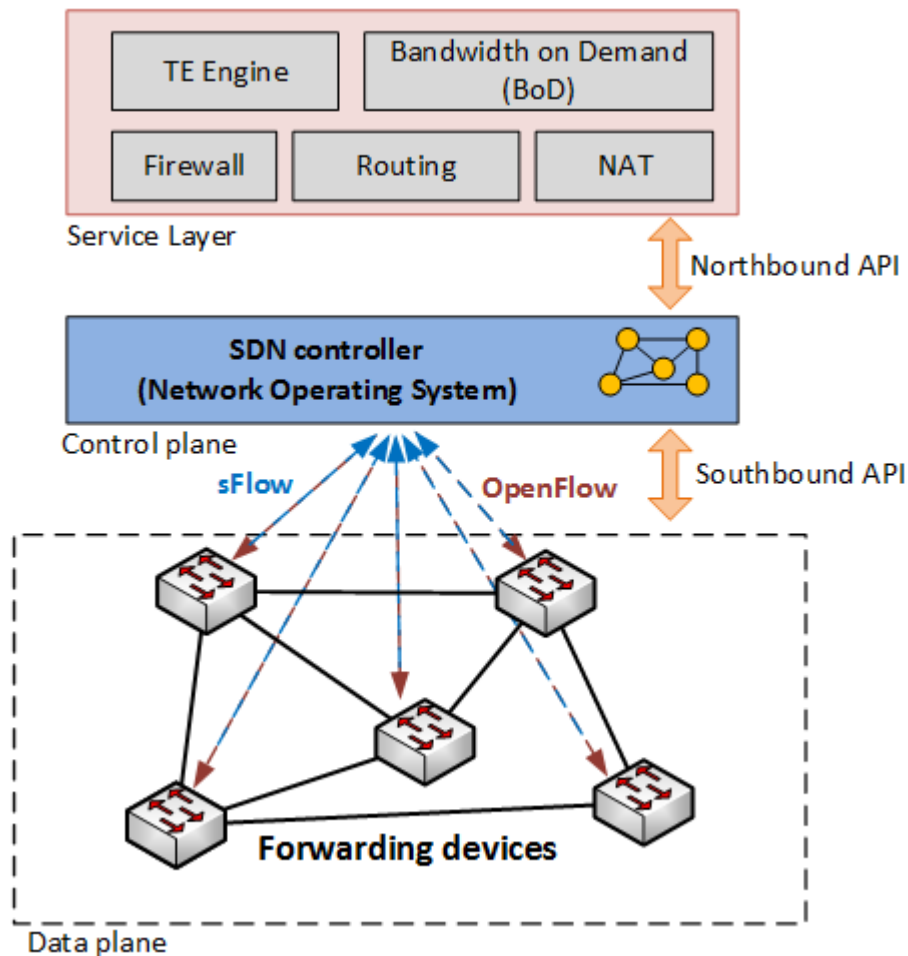


Figure 22. SDN architecture

SDN implementation also enables a set of novel functionalities and a few implementation examples are as follows:

- network virtualization: the idea of dividing a physical network into multiple virtual networks becomes easier regarding the implementation and the operational aspects compared to the case of traditional networks; thus, SDN enables, in comparison with existing network virtualization technologies, a more complex virtualization where the entire network is abstracted and represented as a single switch; moreover, the virtual network operator (the one using the virtual network provided through SDN) can easily manage its network using policies provided on top of the switch virtual abstraction;
- dynamic network access control: considering that every new connection or traffic exchange has to be notified in the SDN controller, unless rules were proactively added in the OF agent, a dynamic network access control can be provided;
- bandwidth on demand (BoD) services: on-demand connections established by the customers via a bandwidth scheduler application deployed over an

SDN controller; connection parameters can be given over the northbound API [74];

Within an SDN/OF environment the network connectivity is not layer-based but it considers the concept of flows. Thus, a flow defines a sequence of packets with common characteristics requested to be forwarded between a source and a destination node. From an OF point of view, the flow is defined as a combination of a 12-tuple (L2, L3 and L4 headers) which form a single flow definition based on the corresponding headers. This flow definition is added in a flow table of the OF Agent (e.g. OpenFlow switch). New extensions of the OF protocol, enable matching not only on L2-L4 header fields but also on lower layer header fields (L0-L1), making it feasible for controlling both packet switched and circuit switched network domains. For identifying a circuit switched domain, a 5-tuple field corresponds to an optical flow. Starting with OF version 1.0 draft 0.3 [75], OF standardization considered the components and the basic functions of circuit switched domains based on time-slots, wavelength and fibers.

In [76] and [77], a control plane architecture based on OF for optical SDN was proposed. The solution is based on extended OpenFlow controller and thanks to OF it is able to abstract the switching entity and the transport format of different technological domains (i.e. Flex-Grid to Fixed-Grid, Flex-Grid to Packet Switched and Fixed-Grid to Packet Switched) in the form of generic flows and using multiple intra-domain flow tables (used to configure the network elements). A novelty of the solution is that it utilizes an inter-domain flow table, which enforces the cross technology constraints for bandwidth allocation when a connection has to cross from one technology domain to another (e.g. Flex-Grid to Fixed-Grid). Simulations in [76] show also that when comparing a hybrid GMPLS-OF implementation vs pure OF architectures, significantly lower set-up times are achieved for the latter choice.

In [78] a review of benefits and challenges for extending SDN concepts to transport network architectures is provided including optical channels and fiber switches, circuit switches and sub-wavelength optical bursts. The review emphasizes the additional challenges that an optical transport network has to face in an SDN environment due to the need to consider physical constraints (optical signal power, bandwidth availability, bandwidth granularity, etc.).

In [79] the first demonstration of a fully integrated SDN-controlled bandwidth-flexible and programmable Space Division Multiplexing (SDM) optical network is detailed. The demonstration includes three Architecture on Demand (AoD) nodes, which are linked by two Multi-core Fibers (MCF) carrying sliceable spatial superchannels. A novel SDM flow-mapper is proposed and a multi-dimensional bandwidth slicing service is able to map the network application requirements to the spatial superchannel slices and switching technology available in the AoD nodes.

An interesting approach is detailed in [80], where an OF-based control plane architecture for spectrum sliced elastic optical network, entitled “OpenSlice”, allows dynamic end-to-end path provisioning and IP traffic offloading. Thus, a Multi-flow Optical Transponder (MOTP) [81] is used in order to identify packets of incoming IP

flows according to their destination addresses and/or VLAN tags in order to split them into several sub-flows. Moreover, the architecture considers Bandwidth Variable Wavelength Cross-Connects (BC-WXCs) and together with the MOTPs they are connected by OpenSlice extensions and controlled by a NOX controller [82]. Experimental results show that the OpenSlice architecture is able to provide lower path provisioning latency when deployed in a network with average paths longer than 3 hops while for smaller network spans a GMPLS-based control plane has a better performance.

In [83] a novel implementation of a control plane based on a stateful PCE working as an OF controller (entitled SPOC) is proposed in order to handle Flex-Grid architectures. The controller runs RMSA algorithms while the service establishment and tear-down is done by PCEP (Path Computation Element Communication Protocol) protocol with specific extensions. In [84] a large-scale Flex-Grid optical network testbed with 1000 virtual optical transport nodes was deployed in order to evaluate the performance (i.e. scalability, bandwidth limitation and restoration time) of SDN based architectures. The work in [85] focused on moving from the common case of deploying Coherent Optical OFDM (CO-OFDM) transmission to Direct-Detection Optical OFDM (DDO-OFDM) with the purpose of using a simpler hardware and software implementation. The outcome is the demonstration of a low-cost solution for elastic optical networks implementation mainly for short to medium sized networks.

There are a large number of different implementations and experiments around the centralized control of optical transport networks based on SDN (w/o OF). However, there are also multitudes of challenges that need to be addressed by the research community before having a mature solution:

- Scalability issues in large networks (carrier-networks) with a high traffic dynamicity and heterogeneity;
- Security issue on how to handle 3rd party service deployment on a carrier-network;
- Single-point of failure due to the presence of a single (or few) controller;
- Increasing operational costs due to the need to provide a different software-oriented expertise in carrier-networks organizations;

Centralized control plane implementations and specifically SDN/OF based solutions are proposed in support of deploying Flex-Grid enabled elastic optical networks as a competitor for distributed GMPLS-based control plane framework. Despite the many advantages that an SDN-based control plane provides for the future optical transport networks, only the future research will show whether this promising solution becomes the next generation of control planes in carrier networks.

5.3. Energy efficiency based on Elastic Optical Networks

Energy consumption in telecommunication networks represented a key interest for the research ongoing in the recent past. According to [86] energy efficiency becomes a critical aspect when relating to economical perspectives:

- ➔ 27% increase between 2012 and 2016 of network energy use;
- ➔ 75% increase of global GHG emissions due to ICT between 2002 and 2020;
- ➔ Internet is the 5th energy consuming source;
- ➔ 75% of the energy bill of telecom operators is given by the network;
- ➔ The energy bill represents between 7 and 20% of the operators OPEX;

Moreover, according to the study performed in [87], apart from the main sources of energy consumption such as data centers and access networks, the optical network starts representing one significant source for the overall operator's network energy consumption as shown in Figure 23.

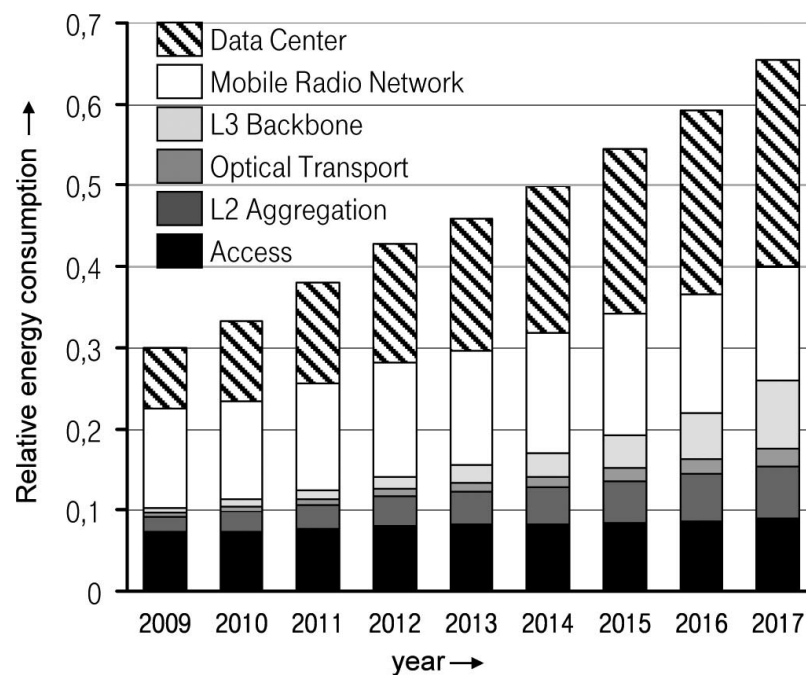


Figure 23. Structure of energy consumption in an operator's network [87]

Figure 23 also shows that an increase in energy consumption of approximately 10% is experienced between 2009 and 2017.

There are different approaches for measuring the power consumption of a network according to [88] which defines the energy efficiency metric as the ration between the functional unit (e.g. total amount of transported data) and the energy necessary to deliver the functional unit (total energy consumed). In this work, the following power/energy measurements are taken into consideration:

- Power per transported data traffic (Watt/bit/second): considers the peak power of the network and the amount of transported traffic; however, this cannot consider the eventual usage of sleep-mode strategies for disabling certain elements in the network;
- Energy per processed data volume (Joule/bit): considers also the impact of sleep-mode strategies and other variations of power consumption over a certain period.

The goal of energy efficiency studies in ICT is to both propose new strategies for improving the energy efficiency as well as de-couple the increase of power consumption from increase in traffic demand. The reduction of energy consumption refers to different layers in the network and the focus in this work is on the core optical transport network.

There are at least three main factors, which drive the energy reduction strategies in optical transport networks:

- **Traffic growth and overprovisioning**

The continuous traffic growth experienced by core optical networks determines the need of using overprovisioning when deploying new resources. Hence, not only that traffic grows and has time variations but the commissioning of new network resources is done at regular intervals (e.g. per quarter, semester, year etc.). This requires the network operator to deploy more resources than the actual predicted traffic demand during the period between two consecutive commissioning activities. Hence, according to the work in [89], capacity overprovisioning has to enable sufficient capacity on the links allowing the network to cope with any kind of overload such as: overload given by statistical variations of the normal traffic matrix; overload given by traffic shifts due to routing mechanisms; or overload due to redirected traffic given by network restoration configurations.

The impact of overprovisioning in terms of energy efficiency relates to a very inefficient utilization of the resources. Improvements can be suggested for overprovisioning planning by using elastic optoelectronic devices, which can tune their capacity according to the traffic demand or temporary overload.

- **Peak vs average traffic variations**

Despite the fact that optical networks are quasi-static (all the network resources are powered considering the peak traffic and independent from the variation in transported capacity), in order to improve energy efficiency, the usage of the optical resources should be placed in accordance with the requested traffic. Thus, in different operator networks in Europe, different fluctuations are observed as the ones presented in [90] where day-night traffic fluctuations in aggregated core links were used in

order to adapt the usage of the optoelectronic interfaces. Traffic values for 24h variations were considered for Orange network, Amsterdam international exchange (IX) point and DT (Deutsche Telekom) network from [18], [91], and [92] as shown in Figure 24:

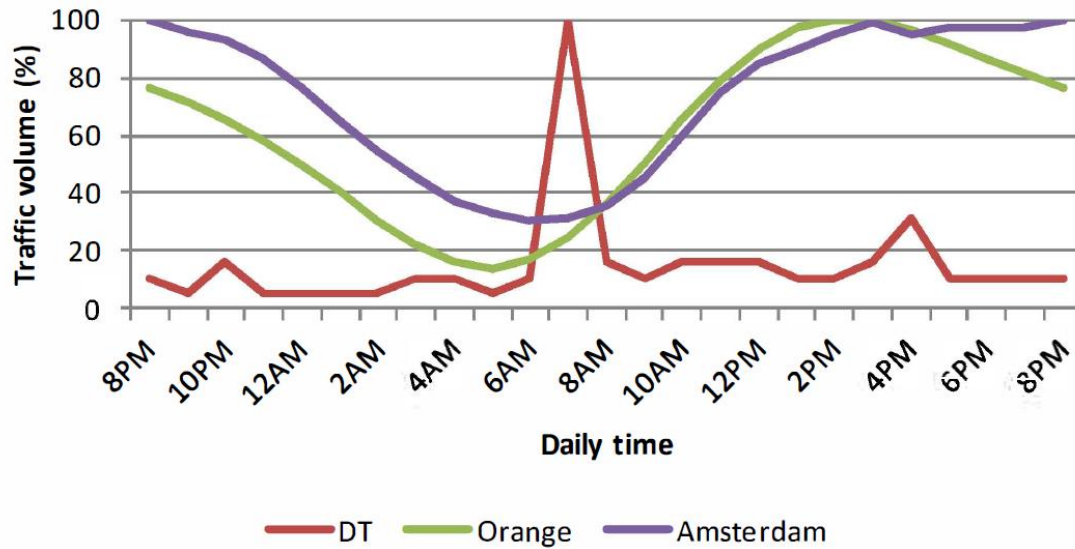


Figure 24. Daily traffic variations measured for different network operators [90]

Hence, according to Figure 24, while all three networks achieve a maximum of 100% in traffic volume, the minimum values are 14%, 30%, and 5% for Orange, Amsterdam IX and DT network respectively while the average traffic volume is 61%, 72% and 15% respectively. It can be observed that depending on the network characteristics, there can be a very high peak to average traffic ratio (e.g. for DT network) and in such cases the fact that the network is powered up always for the case of 100% traffic volume determines a very inefficient power consumption and resource utilization.

- **Service protection and survivability**

Survivability represents a key feature in today's and future optical networks [93] and it affects significantly the energy efficiency. Dedicated protection schemes such as 1+1 or 1:1 are based on the idea of pre-reserving resources in parallel with the working path and thus be able to recover fast in case a failure occurs. This demands a significant amount of extra resources and extra-consumed power since the amount of resources powered on in a protected scenario is often at least doubled. The reason for this is the fact that the working path is the optimum path while the protection path is often longer (in terms of hops or distance). This determines a very inefficient usage of the resources and power consumption and leaves space for significant improvements.

When elastic optoelectronic devices are taken into account, the power consumption can be optimized by using the capability of placing certain elements in the protection path in low power modes (e.g. idle or off).

There are two main approaches used for energy reduction of optical transport networks: sleep-mode strategies, which try to place different elements in the network at lower power states and rate reduction strategies, which try to decrease the symbol-rate of the different active elements in order to reduce their power consumption.

5.3.1. Sleep-mode strategies

Sleep-mode approaches represent a straightforward direction in optical transport network for reducing energy consumption. Hence, a strategy to improve the energy efficiency in future optical transport networks is to provide the power according to the supported traffic variations. Most approaches are focusing on link amplifier sites and optoelectronic devices (OEs) – transponders and regenerators, to be placed in different sleep modes.

The approach of placing link amplifier sites in sleep mode refers to switching off optical amplifiers on unused links in the network with the purpose of reducing overall power consumption as described in [94]. This solution assumes the fact that optical amplifiers can be placed in sleep mode and that they can be switched in a very short time to active mode when a new connection is requested. However, no technology has yet been proposed so far for changing the states of the amplifiers along an optical link. Moreover, in a long-haul link, when a high number of optical amplifiers have to be sequentially activated, the total time for waking up all amplifiers would surely become a limit factor for protection links.

The approach of placing optoelectronic devices in sleep mode refers to switching off unused OE devices in the network with the purpose of reducing overall power consumption as described in [95]. According to [95], transponders and regenerators can be placed in three different power states: up, down and idle (as shown in Figure 25). In Idle state, the optoelectronic devices are not operational but placed in semi-powered state, which allows a fast switch to up state (tens of milliseconds) due to keeping on the components, which require thermal stabilization.

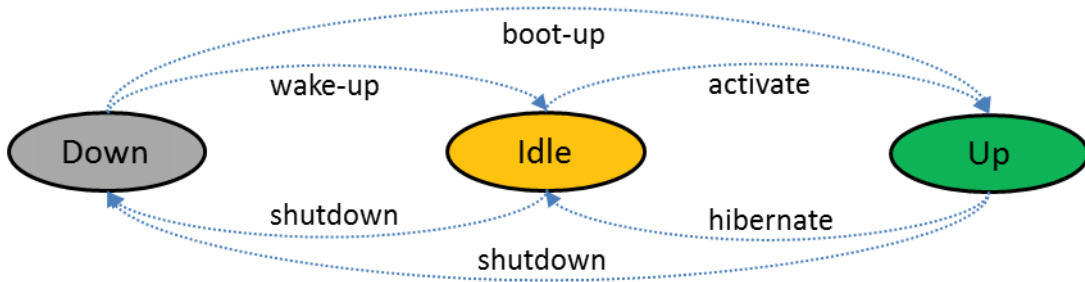


Figure 25. Sleep-modes transition for opto-electronic devices [95]

An example of power reduction given by sleep-mode state of regenerators and the ability of using elastic optoelectronic devices is given in Figure 26 where the variation in incoming bitrate is considered and the channel data-rate is reduced from 100Gb/s to 50Gb/s from day to night re-configuration. Hence, when during the night the channel is lowered to half the bitrate, also the modulation format is changed and due to a longer reach assigned to PDM-BPSK (compared to PDM-QPSK) the regenerator can be by-passed and set in OFF or IDLE mode for reducing the energy consumption during the night time.

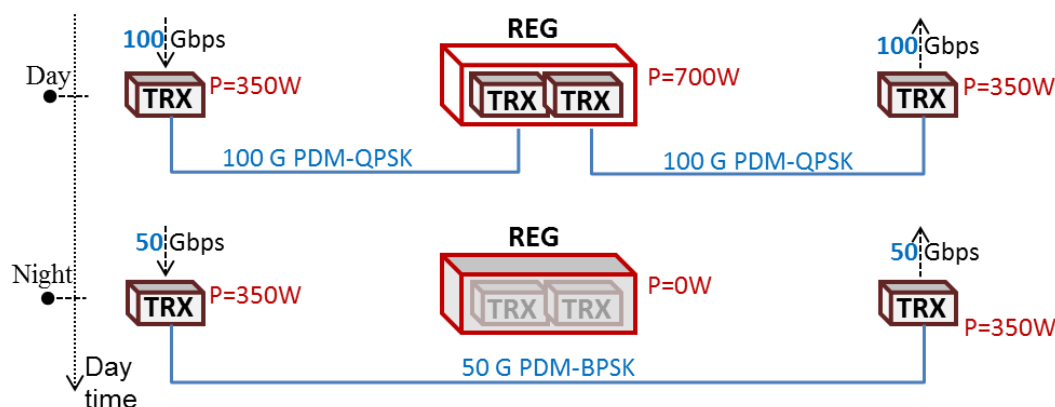


Figure 26. Reduction of power consumption due to sleep-mode of regenerators during night time.

Work in [96] shows an analytical comparison between the two approaches: link vs. optoelectronic device sleep mode approaches and results show significantly higher savings for the second approach which is also the one investigated during the work in this thesis.

5.3.2. Data-rate adaptation strategies

Another approach for energy efficiency refers to varying (and lowering when possible) the symbol-rate on network elements with the goal of reducing their power consumption. As shown in [97], flexible optoelectronic devices are composed of parts which are rate-dependent (i.e. framer and deframer of the client side, Forward Error Correction FEC module and Digital Signal Processing DSP module) and others which are rate-independent (i.e. client-card; laser and drivers associated to E/O modulation; local oscillator, photodiode and analog to digital convertor ADC associated to O/E receiver). Thus, the power consumption of an elastic transponder could vary between 227 and 350W while for an elastic regenerator the variation is between 209 and 414W depending on the selected symbol-rate configuration [97].

An example of power reduction given by rate adaptation and the ability of using elastic optoelectronic devices is described in Figure 27 where the variation of

incoming bitrate is considered and the channel data-rate is reduced from 100Gb/s to 50Gb/s from day to night re-configuration. Hence, during the night when the channel bitrate drops to half value, the channel symbol-rate is decreased and reconfigured from 28Gbaud to 14Gbaud, which in turn determines a decrease in the power consumption of each active optoelectronic device along the path (i.e. both transponders and regenerators decrease their power consumption).

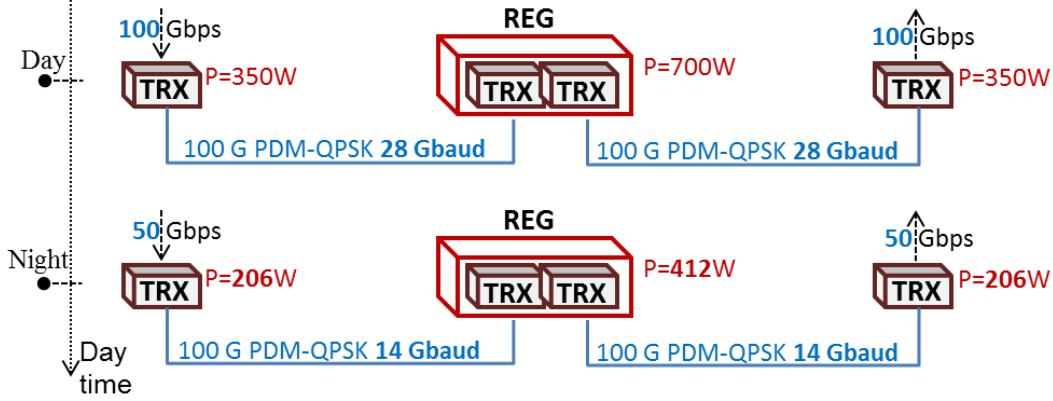


Figure 27. Reduction of power consumption due to rate adaptation of optoelectronic devices during night time

Results in [97] show that up to 30% average power savings can be achieved during the day by applying symbol-rate adaptation strategies together with sleep-mode capabilities. However, in such scenario of combined rate adaptation and sleep-mode capabilities the gain comes with an expense of a 48% extra cost. Moreover, a quasi-optimal power savings result (approx. 26%) is obtained when using only rate adaptation (without sleep-mode capabilities) with no additional expense in terms of optoelectronic interfaces.

III. Methodology

Research problem

The research work performed in this thesis was initiated from the novel concept of elastic optical networks and the need to have a corresponding control plane, which allows investigating realistic case studies for the introduction of elasticity in core optical networks. Initial literature research revealed a lack of support and documentation regarding the extended functionality for GMPLS-based control planes concerning the control of elastic optical networks. An in-depth study of OSPF-TE and RSVP-TE standardization and functionality linked to the description of elastic optical networks concept led to the conclusion that Flex-Grid represents a sensitive aspect within the road map of introducing elastic optical networks. IETF CCAMP meetings initiated the discussions for a common approach on handling Flex-Grid attributes in a control plane framework. Starting from the conclusions of initial CCAMP meetings the research was directed towards finding optimized solutions for enabling both OSPF-TE and RSVP-TE to handle the Flex-Grid parameters.

Once the requirements for a Flex-Grid enabled GMPLS control plane were in place, the research orientation moved towards the effectiveness of a Flex-Grid environment and thus the fragmentation problem revealed as a primary issue.

The need to have a control plane with complete elastic capabilities led the research activity towards the architecture of elastic optoelectronic devices where the contribution of our partners in the Celtic Elastic Optical Networks (EO-Net) Project represented a main source of inspiration. The consequence was the investigation of possible solutions to enable OSPF-TE and RSVP-TE protocols for handling elastic parameters (i.e. modulation formats and symbol-rates).

At the moment when the control plane was clarified in terms of required extensions for Flex-Grid and elastic parameters, the focus moved towards evaluating possible improvements that elastic capabilities could bring in energy efficiency of a core optical network. The energy savings considered the unexploited opportunities given by predictable traffic fluctuations and traffic growth in aggregated core optical links. The traffic variation was inspired by real-time measurements from NORDUnet core optical network.

The possibility to reduce energy by tuning the elastic parameters of optoelectronic devices together with sleep-mode capabilities revealed significant amount of possible power savings in different scenarios. Moreover, the resiliency requirements and service differentiation were introduced in order to find other uses cases, which emphasized the efficiency of elastic optoelectronic devices.

The overall research succeeded in answering a multitude of questions about the implementation of Flex-Grid and elastic optoelectronic devices together with energy saving strategies within a standard-compatible distributed GMPLS-based control plane while analyzing dynamic network scenarios.

Solution design

The research work performed during this thesis was mainly based on developing network scenarios and protocol extensions over the discrete event-driven simulator OPNET Modeler [98]. OPNET Modeler allows simulating complex networks and thus real-case scenarios implementing network architectures such as COST37 [99] or NSF [100] networks, which were used for analyzing the proposed mechanisms.

Implementation

The work in OPNET Modeler started initially from an already existing distributed GMPLS model [101] from DTU Fotonik, which was capable to handle dynamic connection establishment including network discovery, wavelength reservation (via RSVP-TE) and information dissemination (via OSPF-TE). The model was then expanded in two phases. OSPF-TE and RSVP-TE were designed in OPNET Modeler based on the *Finite State Machine (FSM)* technique while all the states and the state transitions describing the functionality of the protocols or the proposed extensions were coded in C/C++.

In the first phase, Flex-Grid capabilities were added at the network discovery layer in order to allow all the elements to handle every fiber at a higher spectrum granularity as well as defining the spectrum slots concept for all the fiber links and node ports. Moreover, OSPF-TE was extended in order to allow different procedures for advertising the availability information associated to the Flex-Grid spectrum slots. Due to the high number of spectrum slots present at high granularity configuration in Flex-Grid, various challenges were considered on how to realize the dissemination process in a scalable way. RSVP-TE was extended as well concerning Flex-Grid capabilities, allowing *Path*, *Resv* and other *Error* messages to identify and transport information referring to spectrum slots and spectrum slices. The de-fragmentation procedure, which was specifically focused on RSVP-TE message exchange, required additional extensions to the signaling process in order to enable *Trigger* messages for handling the de-fragmentation procedure.

In the second phase, optoelectronic devices' (transponders and regenerators) elastic parameters were introduced in the model with the goal of enabling energy efficiency strategies. The capabilities of handling a set of modulation formats and symbol-rates at every node were added within the network discovery process. The OSPF-TE was enabled to advertise every node capability in terms of elasticity parameters as well as available number of transponders and regenerators. RSVP-TE extensions represented the main focus in the second phase. *Path*, *Resv* and *Trigger* signaling messages were extended to encapsulate elasticity parameters of optoelectronic devices as well as identifying sleep-mode states and different configurations related to energy efficiency strategies.

An important aspect in the implementation was represented by the traffic generator, which was implemented as a distributed source of incoming demands in every node in the network with dynamic connection requests following an exponential distribution of mean inter-arrival time and connection lifetime. In case of Flex-Grid simulations,

the requested connections data-rates were considered constant during the entire life of the connections and each simulation was run until the network reached a state of convergence (a high enough number of connections was requested in every source node with the configured mean inter-arrival time and duration). In case of energy efficiency simulations the requested connections data-rates were considered variable (periodical fluctuation and overall growth) based on pre-defined variation path (added as input *.txt files with values inspired from NORDUnet real-time measurements in aggregated core links) and the considered simulation time was selected to 365 days.

Verification and validation

For verification purposes every network scenario was run at simplified functionality (e.g. every link was initially considered as having 1 wavelength available while in final simulations every fiber link was configured with 80 wavelengths) and with minimum number of variable parameters in order to prove the proper functionality of the system. Moreover, in order to ensure the individual functionality of the protocols, the network was simulated in simplified version while only running RSVP-TE, OSPF-TE, or network discovery functionalities. Similarly, in order to verify the correct behavior of Flex-Grid and elastic parameters, after the coding phase was completed, the network was simulated in simplified configurations such as using a single modulation format and single symbol-rate. Moreover, it was verified that at a 6.25GHz Flex-Grid set-up, when all connections are requested with the same spectrum requirement of 50GHz, the results correspond to the ones of a 50GHz Fixed-Grid scenario with the same random demand distribution.

In order to validate the results, a high number of random seeds (varying between 20 and 100) were used and results were considered within a confidence interval of 95%. Moreover, simulations were consequently run with different (increasing complexity of) modulation formats to validate the limiting optical reach as well as different (increasing) symbol-rates to validate the raise in the power consumption of all optoelectronic devices along the path.

Results

The process of collecting results was based on defining simulation scenarios with specified parameters according to the pre-planned strategy. The results were collected and exported in Microsoft Excel and extracted as scalars or graphical representations. Based on OPNET Modeler functionality, it was able to run the same scenario with changed parameters while always keeping the same random distribution of the demands – thus allowing a realistic comparison for the variation of individual parameters.

IV. Conclusions and Outlook

Core optical networks are a sensitive part of the roadmap towards developing the transport networks of the future. A new set of challenges are faced in the core domain given by its nature of transporting large amounts of aggregated traffic between separated domains, metro and access networks or data-centers across large geographical areas. Due to the continuous development of the access technologies and of the user devices and applications, the amount of traffic that users and end terminals are generating consists of a strong increase, which has an impact on designing the core transport network. The increase in volume of transported traffic, the more heterogeneous behavior of the requested connection demands as well as the increasing energy consumption and CO₂ emissions represent the main challenges, which drive the re-thinking of the core optical transport network.

There is also a sensitive trade-off that a network operator has to consider when upgrading its existing optical network and often the profit margins are small enough that they require limited investments in capacity increase or technology update. Moreover, as new disruptive services (e.g. Netflix) acquire more geographical area coverage and increase in number of customers, the network operators are suddenly forced to cooperate with the specific service provider and share the costs of the network upgrades which was never the case before. Services that drive the network development become today's reality and network operators have to reinvent themselves in providing a network service in a profitable manner.

This chapter summarizes the results presented in this thesis and highlights some future research perspectives in the area of elastic optical networks while focusing on four main aspects:

- ➔ Elastic optical networks;
- ➔ Flex-Grid architecture;
- ➔ GMPLS-based control plane in support of Flex-Grid and elastic optical networks;
- ➔ Energy efficiency strategies based on elastic optical networks under a GMPLS-based control plane;

This thesis makes several contributions in the areas indicated above while it addresses the current and future challenges in the area of core optical transport networks.

Elastic optical networks

Elastic optical networks represent the medium term solution proposed in the near past to cope with the challenges faced by core optical networks in terms of capacity and flexibility. Elastic optical networks concept is based on the idea of varying multiple physical parameters at the optoelectronic layer (e.g. modulation format, symbol-rate,

FEC code, channel spacing) in order to precisely adapt the optical connection parameters to the properties of the traffic demand. In this case, significant amount of optical capacity that was wasted in classical deployments could be used and the entire optical transport network can be optimized. Moreover, by enabling flexibility at the optical layer, the transport networks acquire a level of intelligence, which is required for performing multi-layer network optimization.

The elastic optical networks concept is based on the development of proof-of-concept elastic optoelectronic devices (i.e. elastic transponder and elastic regenerator). Such devices were proposed within “Elastic Optical Networks (EO-Net) Celtic Project” and their characteristics represented the foundation of the implementation and numerical simulations performed in the work of this thesis. It is also important to note that elastic optical networks can refer to two different ways of using the optical resource in defining a channel. One is by using a single-carrier solution and varying the spectrum of that single channel as well as the rest of the optical parameters. The other is by using a “super-channel” solution based on OFDM or Nyquist-WDM which enable a set of contiguous sub-carriers individually modulated and controlled as a single channel. In this work, it was considered only the first approach where single-carrier channels were deployed.

Future research work has to converge towards a standardized way of defining the granularity of elasticity at different parameters and to propose a mature approach for the architecture of elastic transponders and regenerators as well as elastic aggregation interfaces.

Flex-Grid architecture

A first challenge raised by the introduction of elastic optical networks is how to manage a flexible optical spectrum system. By flexible spectrum, a new structure within the optical spectrum of a fiber is proposed by defining and using very narrow (e.g. 6.25GHz) spectrum slots. Thus, a set of contiguous spectrum slots can form a variable size spectrum slice, which can be allocated to any optical connection in a flexible manner. Two main issues are faced when introducing Flex-Grid in current optical system and they were both investigated in current thesis while solutions were proposed based on the support of an extended GMPLS control plane.

The first issue is about finding solutions to optimally signal and advertise the information about spectrum slots statuses in a large network. This needs to consider the fact that the number of spectrum slots is much higher compared to the number of advertised channels in a classical fixed-grid case (e.g. 6.25GHz grid vs. 50GHz grid results in 8 times more information to be disseminated). Moreover, new ways to transport and identify the proper information in Flex-Grid via the signaling and routing mechanisms are needed. Within the work of this thesis, both RSVP-TE and OSPF-TE extensions were proposed and different solutions were analyzed and numerically simulated in order to find optimum configurations for running Flex-Grid. RSVP-TE PATH and RESV messages were extended to include “generalized labels” while reservation mechanisms were enabled to handle Flex-Grid requirements of

contiguous slots. OSPF-TE dissemination of spectrum slots statuses was proposed to use a bitmap encoding for an optimum trade-off between the “freshness” of the available information and the load of the control plane.

The second issue faces the idea of fragmentation, which is specific to Flex-Grid architectures in a similar way, as it exists in computer memory systems. Moreover, when running Flex-Grid in a very dynamic environment the fragmentation can become an issue that decreases significantly the effectiveness of the solution, and eventually makes it unattractive compared to the classical fixed-grid architecture. Thus, a de-fragmentation mechanism was proposed based on RSVP-TE *Trigger* messages which are able in a hitless manner (and using a periodical update) to re-assign the spectrum allocation of a connection in such a way that it always minimizes the fragmentation of the spectrum. Future work on de-fragmentation aspects is still required because fragmentation is very dependent on the network scenario and traffic characteristics and thus different solutions should address different cases in order to have a highly scalable control plane. Moreover, additional studies are required in order to identify improved methods for spectrum allocation, within RSA algorithms and requirements such as scalability and complexity have to be prioritized.

Flex-Grid architecture will most likely be deployed in parallel with existing Fixed-Grid infrastructure due to cost optimization. Hence, it is important that the proposed Flex-Grid solutions take into account the need to be compatible with existing 25, 50, or 100 –GHz Fixed-Grid networks.

While Flex-Grid has various applicability scenarios, more studies are required in order to quantify the gain of implementing mature solutions in operator networks where eventually more capacity could be exploited over the existing infrastructure. Also, it has to be taken into account that Flex-Grid is a good solution to enable very high-speed channels within submarine communications allowing connectivity of 400Gb/s, 1Tbps or even more within a single channel while assigning the proper spectrum resource.

Energy efficiency based on elastic optical networks

Energy efficiency is another challenge that raises more and more concerns in core optical networks due to the increase of power consumption, which comes as an outcome of the increased number of fiber links, and optoelectronic devices commissioned in support of capacity increase. However, traffic in aggregated core links experiences predictable traffic fluctuations and predictable traffic growth, which has to be exploited in order to optimize the usage of the optical resources and the power consumption. Thus, thanks to the ability of tuning the modulation format when using elastic optoelectronic devices together with enabling sleep-mode capabilities, regenerators along the optical path can be bypassed and energy can be saved. Moreover, the ability to vary the symbol-rate allows the reduction in power consumption of every optoelectronic device along the path when data-rate decreases and a re-configuration is performed. The proposed solutions in this thesis consider extensions to the GMPLS-based control plane by enabling RSVP-TE *Trigger*

messages to perform verifications and changes with a certain update period as well as enabling a policy controller to react and take optimized decisions on the type of re-configuration that has to be done. Thus, according to the work performed in this thesis, by adapting the optical connections data-rates and using sleep-mode capabilities according to the data-rate fluctuations and expected growth the power consumption can be highly optimized.

When analyzing power consumption it is important to note that a significant impact is given by the deployment of resiliency, which often requires duplication of resources in the protected scenarios compared to the unprotected ones. Thereby, in case of resilient scenarios the tuning capabilities of elastic optoelectronic devices together with the sleep-mode attributes allow for a significantly improved energy efficiency compared to the unprotected scenarios. In addition, it is important to note that depending on the network characteristics (geographical spans, number of nodes, average link length etc.) the efficiency of the energy reduction strategies can significantly vary depending on the chosen solution.

Moreover, future work has to investigate advanced methods on predicting the traffic variations in order to enable a proactive approach on channel re-configurations rather than a reactive solution as it is proposed now.

Distributed GMPLS vs. centralized SDN-based control planes

GMPLS-based control planes are not the only solution to handle Flex-Grid and elastic optical networks functionality but a significant part of the research today focuses on centralized SDN-based solutions often used in conjunction with OpenFlow used as southbound API. GMPLS-based control planes are characterized by a distributed deployment as they need an instantiation in every node for controlling functions while the signaling is performed hop by hop in a successive manner and the routing follows a flooding approach while the routing information converges in every node. GMPLS can also work partially centralized when deployed together with a Path Computation Element (PCE). In this case, a single entity centralizes the path computation functions and routing information dissemination while only leaving the signaling to be performed in a distributed manner.

During this work, the focus was placed on the development of a GMPLS-based solution because of a double motivation. Firstly, the knowledge in the department and previous work was concentrated on GMPLS control planes and contribution on top of that could be efficiently performed. Secondly, GMPLS is a mature solution for controlling large core optical networks – it has only started in the near past to be largely adopted by network operators while SDN-based solutions are still a future direction on research and it is not yet confirmed whether they are scalable or operationally and economically feasible for implementation in large carrier networks. Hence, GMPLS-based control plane solution was considered in this work as being a rather practical approach on facilitating the introduction of elasticity and Flex-Grid in currently deployed core network control planes. Future work in the area considers also hybrid solutions, which take into account a locally distributed approach using

GMPLS and a globally unified control using SDN-based solutions in order to combine the advantages of the two for having a scalable and operationally feasible solution.

The research work performed in this thesis revealed significant potential for the introduction of elastic optical networks together with the deployment of an extended GMPLS-based control plane. Increased capacity over existing optical infrastructure, an increased flexibility, and improved energy efficiency are three main arguments, which make elastic optical networks a promising solution for the future core optical network deployments.

Appendices

A. GMPLS control plane extensions in support of Flex-Grid enabled elastic optical networks

GMPLS control plane extensions in support of flex-grid enabled elastic optical networks

Ioan Turus, Anna Manolova Fagertun, and Lars Dittmann

Technical University of Denmark

2800 Kgs. Lyngby, Denmark

E-mail: iotu@fotonik.dtu.dk

Abstract

We develop a GMPLS control plane handling flex-grid enabled Elastic Optical Networks. The implementation is realized in OPNET Modeler event driven simulation tool with focus on developing and implementing extensions for the GMPLS protocol suite. RSVP-TE extensions address the reservation of generalized labels format and enable enhancements for the wavelength selection procedures. OSPF-TE enables the creation of spectrum databases based on novel LSA sub-TLV attributes capable of advertising spectrum status. Based on the implemented extensions, we propose and evaluate advanced distributed spectrum allocation schemes and strategies for dynamic routing algorithms in support of flex-grid optical networks.

1. Introduction

Network operators are facing today various challenges in the core optical networks with regards to providing and handling capacity. This is due to the continuously increasing capacity demand, of about 2dB per year according to [1], which faces the current rigid optical network deployments. The main solution that operators use for increasing the provided capacity is to deploy more fibers, extend the number of channels within one fiber or use higher modulation formats for the deployed optical channels. However, none of these represent a long term solution and they are not flexible enough to cope with the scenarios where capacity demand experiences high peaks which are significantly higher than the time average of the demanded capacity.

Elastic Optical Networks (EO-Net) represent a solution which enables elasticity at various levels in the deployment of optical resources. EO-Net considers the variation of different parameters of an optical connection such as symbol-rate, modulation format, Forward Error Correction (FEC) codes and spectrum assignment. Based on the flexibility of the optical connection parameters, the network is able to scale up or down resources according to the demands' properties and it allows operators to deploy a more efficient network. Considering the EO-Net architecture, the network does not need to be planned for peak-traffic conditions but ideally it can follow the average of the traffic demands.

In order to enable the elasticity features, one of the first challenges is to provide flexibility in handling spectrum resources. Currently, Wavelength Switched Optical Networks (WSO) architecture follows the standard ITU-T grid specification [2] which defines the 50 GHz constant channel spacing. In order to enable flexibility in the spectrum assignment, ITU-T defines in the edition 2.0 of [2] an extended granularity in the channel spacing, down to 6.25 GHz. This represents the key point of the so called Flex-grid networks

which are associated to the newly defined SSON (Spectrum Switched Optical Networks) architecture [3]. However, by increasing the granularity of the spectrum grid, the complexity of running such network is increased as well and this determines more requirements for the control plane which is running the SSON network.

GMPLS is considered for running SSON based core optical networks as an evolution from WSON networks where GMPLS can already be considered a mature control plane solution. Thus, in order to enable GMPLS to run flex-grid networks, GMPLS protocol suite (OSPF-TE and RSVP-TE) requires a number of extensions to adapt it to the new flexible environment.

This paper presents a detailed OPNET Modeler implementation of the RSVP-TE and OSPF-TE with the required extensions which enable the control of a Flex-grid based Elastic Optical Network. Thanks to the Flex-grid enabled distributed GMPLS control plane, different signaling and routing strategies can be investigated and the control plane efficiency is evaluated in various scenarios. The remainder of this paper is organized as follows: In Section 2 Flex-grid architecture and parameters are described. In Section 3 GMPLS control plane aspects will be analyzed considering the required extensions for enabling flex-grid for both OSPF-TE and RSVP-TE, as well as proposing signaling and routing strategies for improving the control plane efficiency. In Section 4 the OPNET Modeler implementation is presented. Section 5 details the investigated scenarios and results which evaluate the performance of the proposed architecture. The paper ends with concluding remarks regarding the OPNET Modeler implementation and its benefits for further investigating flex-grid and elastic optical networks technology.

2. Flex-grid based Elastic Optical Network (EO-Net)

The Flex-Grid concept considers lower channel spacing compared to the currently used 50 GHz grid. ITU-T proposes different channel spacing values such as 25, 12.5 and 6.25 GHz. The lower bound limit of 6.25 GHz is chosen by taking into account physical limitations and the cost of the current optical filters and Wavelength Selective Switches (WSSs).

The parameters describing the Flex-grid architecture are the following:

- Central Frequency Granularity (CFG) – defines the spacing between two consecutive central frequencies (e.g. 6.25 GHz in Figure 1 for flex-grid example)
- Spectrum Slice Width (SSW) Range – defines the minimum and the maximum size of a Spectrum Slice (e.g. minimum 6.25 GHz, maximum 200 GHz)
- Spectrum Slice Granularity (SSG) – defines the step which gives the possible values for the Spectrum Slice width (e.g. 12.5 GHz step/granularity)

Every Spectrum Slot is identified by its corresponding central frequency. The flexibility in flex-grid environment is provided by the possibility of defining Spectrum Slices which can group a number of contiguous Spectrum Slots. A spectrum slice is defined by using two parameters:

- spectrum slice central frequency (parameter n)
- spectrum slice width (parameter m)

As shown in Figure 1, the orange slice is described by a central frequency $n=-5$ and width $m=1$, while the blue slice is described by $n=2$ and a width $m=4$.

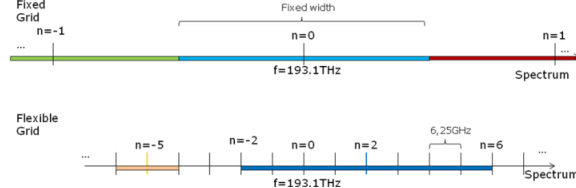


Figure 1: Fixed-grid and Flex-grid architecture

3. GMPLS control plane in support of Flex-grid EO-Net

3.1 RSVP-TE extensions

RSVP-TE is responsible within GMPLS protocol suite for signaling aspects. From a flex-grid perspective, RSVP-TE is required to handle spectrum slots and slices instead of wavelengths. Thus, the label concept has to be generalized to a format which allows the control plane to handle both the fix-grid and the flex-grid channels. As shown in Figure 2, the WSON label format is extended, as suggested in [4], to include a definition for the grid type (e.g. DWDM), the channel spacing or central frequency granularity (e.g. 5 – for 6.25 GHz) and the index of the central frequency of the slice (n).

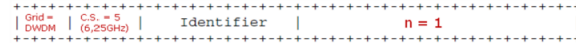


Figure 2: The generalized label format

Moreover, considering the fact that a slice can have variable size (which was not the case for fix-grid channels), apart from generalized labels, RSVP-TE has to carry as well in the *PATH* message the size of the requested slice. The m parameter will be included in the *Tspec* object with the format shown in Figure 3.

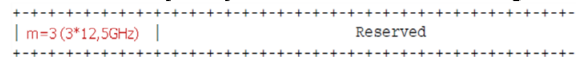


Figure 3: The Spectrum Slice width in *Tspec* object format

RSVP-TE operation will start once the Path Computation engine provides a request for a certain slice size on a predefined path. RSVP-TE will use a *PATH* message to carry the *Tspec* object from source to destination and check in every node all the available Spectrum Slots/Slices that are available and can handle the requested slice size. For every possible set of Spectrum Slots or Slices which are valid for serving the requested slice, the central frequency will be added to the Available Label Set object as shown in Figure 4. The destination node receives all the common central frequencies available to be reserved along the path and based on a local policy decision it will choose one of them and will signalize it back to the source by using the *Resv* message which performs the actual reservation of the specified slice node by node.

The signaling mechanism depicted in Figure 4 describes the distributed GMPLS architecture and the main difference in various implementations is provided by the local policy decision.

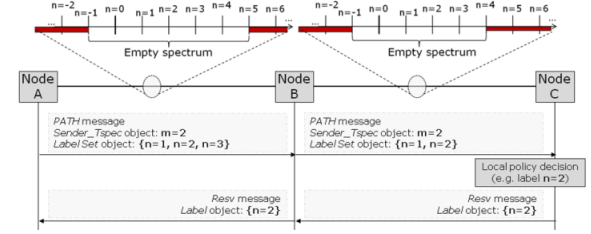


Figure 4: Distributed RSVP-TE signaling in flex-grid networks

For the local policy decision, as part of our work done in [5], we consider three methods:

- *First-Fit*, selecting always the first available central frequency in the label set;
- *Random Assignment*, choosing a random central frequency;
- *Mixed-Fit*, switching between First-Fit and Last-Fit methods consecutively in every node;

3.2 OSPF-TE extensions

OSPF-TE is responsible within GMPLS protocol suite for the routing aspects. In case of flex-grid networks OSPF-TE has to be able to advertise changes that occur in the availability of the spectrum slots. In order to enable this, OSPF-TE Link State Advertisements (LSA) packets will include extended sub-TLVs which can address the status of the spectrum slots.

There are two options we propose in [6] for the format of spectrum slots availability. First option is to extend the Label Set object format for the Inclusive List as shown in Figure 5, and add the state of the slice – free or busy.

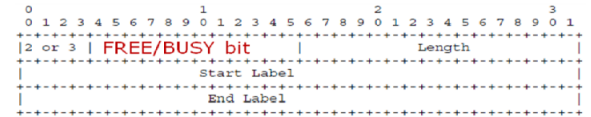


Figure 5: Inclusive List format for Flex-grid Label Set Object

The second option we evaluate is the bitmap encoding instead of Inclusive List for the Label Set format as shown in Figure 6.

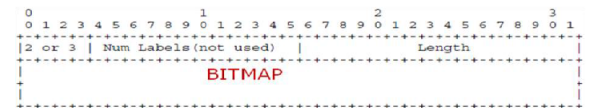


Figure 6: Bitmap encoding format for Flex-grid Label Set Object

An important aspect for the OSPF-TE configuration is the *MinLSInterval* timer value which specifies the minimum time interval where a node cannot send consecutive LSA advertisements. The timer value determines the speed of convergence of the information along the network as well as the load on the control plane.

The information from the LSA advertisements is gathered at every node in a so called Spectrum Database which contains the overall picture of the spectrum status on all the links along the network. This database will serve the Path Computation mechanism in taking optimal decisions for selecting the path.

The Path Computation mechanism will consider a number of routing strategies with the purpose of optimizing the path selection. OPNET Modeler uses by default a method based on Dijkstra graph where the shortest path first algorithm is selected in terms of number of hops. However this is not always the most optimal solution in flex-grid networks. In [6], we propose two strategies called *relaxation graph* and *weighted graph* with the goal of reducing the overall connection blocking.

The *relaxation graph* strategy described by the pseudo-code in Figure 7 is looking into disabling in the source node the links that cannot cope with the requested slice size. Thus, every time a slice is requested, the source node checks the Spectrum Database for all the links in the network if a link has at least one island of m contiguous spectrum slots. If no such island can be found it means that that link cannot handle the requested slice and it is temporarily disabled in the Dijkstra graph of the source node. After all the links are verified, the source node performs the Shortest Path First algorithm on the updated Dijkstra graph.

```

W = total number of Spectrum Slots (or central frequencies) in a fiber
L = total number of links/fibers in the network
m = requested slice size (expressed as number of Spectrum Slots)

for i = 0 to (L-1)
{
    for j = 0 to (W-1-m)
        if (slots from j to j+m are free)
            break;
    Disable in Dijkstra graph link i;
}

```

Figure 7: Relaxation graph mechanism pseudo-code

The *weighted graph* strategy described in the pseudo-code in Figure 8 considers to what extent the links are occupied.

```

W = total number of Spectrum Slots (or central frequencies) in a fiber
L = total number of links/fibers in the network
m = requested slice size (expressed as number of Spectrum Slots)

for i = 0 to (L-1)
{
    count = 0;
    for j = 0 to (W-1)
        if (slot_j is occupied)
            count++;
    Assign in Dijkstra graph weight count for link i;
}
Perform shortest path first (SPF) algorithm on weighted Dijkstra graph

```

Figure 8: Weighted graph mechanism pseudo-code

Thus, the algorithm checks the links occupancy in every source node every time a new slice/connection is requested. The verification is done by using the information from the Spectrum Database. For every link, the number of occupied spectrum slots is computed and the resulted value is assigned to the Dijkstra graph as weight for the corresponding edge (or link). After all edges are updated with the up-to-date weights, the Shortest Path Algorithm is executed and it selects the path with the lowest weight, prioritizing in this way the least loaded links.

4. OPNET Models of the GMPLS control plane for the Flex-grid based EO-Net

The network simulation model has been developed over three layers: network model, node model and process model.

4.1 Network and node models

The OPNET Modeler implementation took into account two different network models as presented in Figure 9 and Figure 10 for the sake of diversity of the network characteristics.

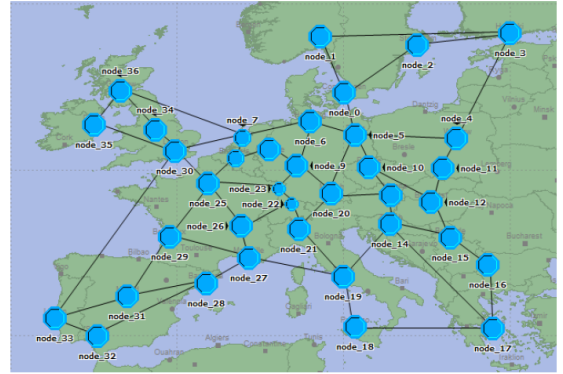


Figure 9: Network model based on COST 266 topology

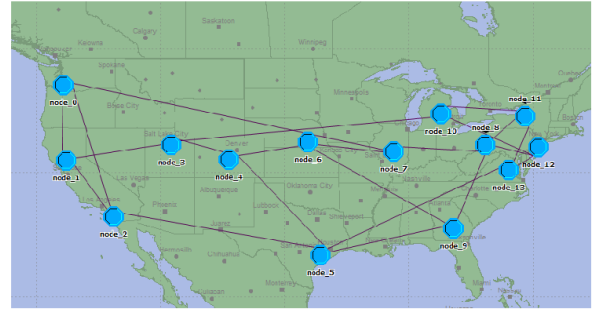


Figure 10: Network model based on NSF topology

In the current implementation and simulation scenarios the COST 266 topology was used for evaluating the RSVP-TE enhancements while the NSF topology was used to evaluate the OSPF-TE extensions.

The node model is shown in Figure 11 and it consists of a connection generator (*ReqGen*), a routing module (*Routing module*), an instance of OSPF-TE, an instance of RSVP-TE and the associated seven receivers (*pr_x*) and transmitters (*pt_x*).

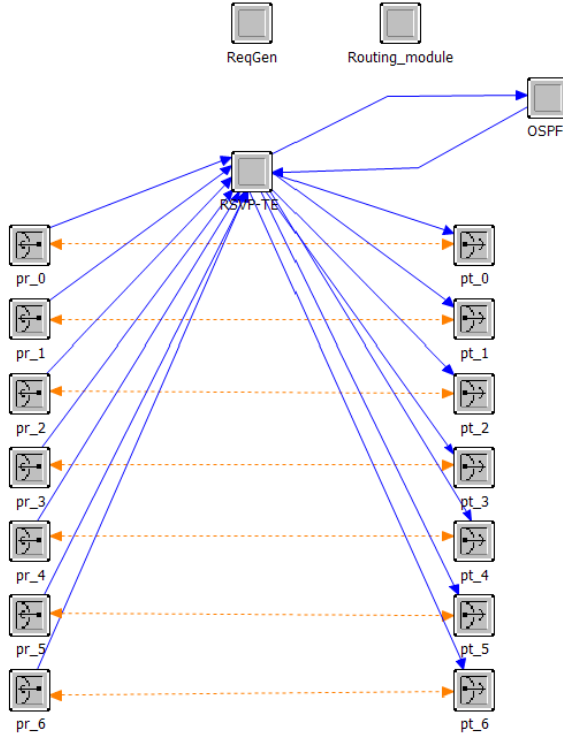


Figure 11: Node model

The connection generator is responsible to create elastic connections with specific properties corresponding to the elastic transponder capabilities described in [7]. The OSPF model is responsible to handle LSA packets and update the Spectrum Database as well as handling the advanced routing strategies. The routing module handles the routing table by associating to every directly connected node the corresponding interface. The RSVP-TE model is responsible for providing a path and handling the *PATH*, *Resv* and the rest of signaling messages required to reserve resources along the path.

Connection generator process model

The Finite State Machine (FSM) describing the *ReqGen* model is shown in Figure 12. The *Init* state handles the variable initialization, statistics definition, attributes retrieval and ends with changing state to *Idle*. In *Idle* state self-interrupts are scheduled according to an exponential distribution defining the Mean Interval Time (MIT) between consecutively generated connections.

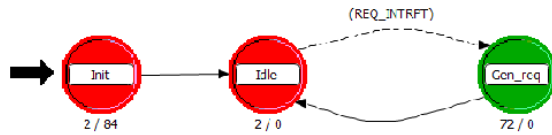


Figure 12: Connection generator model

The parameters describing the connection generator are shown in Table 1. The bandwidth for every connection is uniformly distributed between 0 and 100 Gbps and a round-up is made to

the closest higher level of bit-rate which is available in an elastic transponder according to [7]. 1 bit per symbol is considered and the 4 available bit-rate levels are 25, 50, 75 and 100 Gbps which results in 25% probability of obtaining a connection in one of the four bit-rate or bandwidth levels.

Variable	Value
Flow destination	Uniform distribution (total number of nodes)
Bandwidth	Uniform distribution (0...100Gbps)
Duration	Exponential distribution (mean of given <dur> variable)
Mean Interval Time	Exponential distribution (mean of given <mit> variable)

Table 1: Connection generator parameters

The *Gen_req* state is also responsible to create remote interrupts which send the connections parameters to the RSVP-TE module.

4.1 Process models

The process models used in the current implementation represent an extension of the OSPF, RSVP-TE and routing models from [8]. The models were adapted to efficiently handle flex-grid particularities and their functionality, including the flex-grid specific changes, is described below.

Routing module

The FSM for the routing module is depicted in Figure 13. The model starts with the *Init* state where attributes for the routing or signaling strategies, as well as for the flex-grid architecture are retrieved. The *Init* state is also responsible to associate a Dijkstra graph (made by vertices and corresponding edges) to the implemented topology by creating a routing table. Based on the Dijkstra graph created at this moment, the path computation will be performed for every incoming connection. Once the routing table is constructed, the routing module also triggers the OSPF and RSVP-TE modules by sending remote interrupts.

If the node is enabled in the network, the process moves to the *Operational* state, otherwise it ends in the *End_Sim* state. The *Disable_Edge* state is used for situations where all the resources on one link (spectrum slots) are used and the link/edge has to be disabled from the Dijkstra graph or in case where resources become available and the link can be re-enabled. In such situations, the RSVP-TE is performing a remote interrupt for the routing module and identifies the edge using global variables.

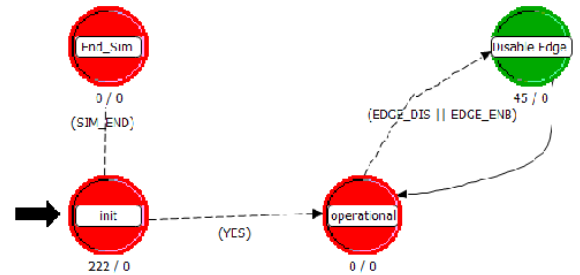


Figure 13: Routing process model

OSPF-TE module

The OSPF-TE module is run once the routing table is initialized in the Routing module and a remote interrupt is received. The role of this module is to be able to create and receive Spectrum LSAs (Extended TE LSAs), update Spectrum Database and confirm the advertisements for the other nodes.

The model implements OSPF version 2 at a simplified format with the purpose of emphasizing the effect of the flex-grid environment in an OSPF/GMPLS based control plane. According to the flex-grid architecture, whenever a connection is set-up or released, a number of spectrum slots are occupied or released as well. This information is required for the rest of the nodes in the network so they can update their Spectrum Databases and provide optimal path computation. Thus, whenever a slice or set of spectrum slots is changing the status, the OSPF module has to create a Spectrum LSA and flood it to its neighbors (according to the OSPF specifications). Similarly, whenever a node receives a Spectrum LSA, it will update its own Spectrum Database and will confirm the receipt to the corresponding node.

The implementation is extended from the one in [8] with a number of additions. According to the OSPF-TE FSM shown in Figure 14, the *Init* state is responsible for variable initialization and attributes retrieval. In state *Begin* the initialization of the neighbors list and links is performed and the process moves to the *Exchange* core state. From this state, the process can switch to one of the three *Create* processes whenever the OSPF process receives an interrupt because of a change in the spectrum of the links directly connected to this node. Depending on the model of Spectrum LSA format that is used (as described in Section 3.2) the process goes to *Create2* or *Create3* states. The only difference between the two states is the format of the sub-TLV that carries the spectrum state information. In the *Create (2 or 3)* state, the Spectrum LSA is created and it is flooded to all neighbors. A sensitive parameter implemented here is the *MinLSInterval* timer which according to [9] defines the minimum period between creating two consecutive LSAs. In case a request arrives for a new LSA before *MinLSInterval* timer passes, the LSA creation is ignored. *Create1* state handles the creation of another type of LSA (Flex-Grid properties LSA) at the beginning of the simulation. This type of LSA is responsible for advertising the flex-grid capabilities and parameters specific for every node. However, in this implementation, this type of LSA is not used because we consider that all nodes in the network have the same flex-grid parameters.

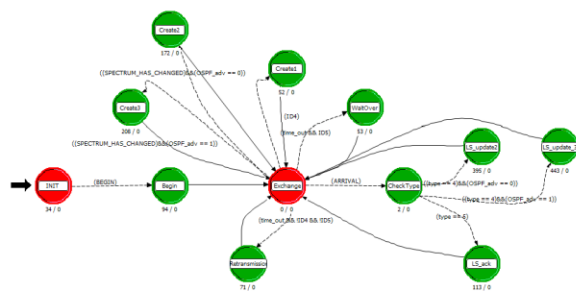


Figure 14: OSPF-TE process model

The *WaitOver* and *Retransmission* states are similar to the implementation in [8] while the *LS_Update2* and *LS_Update3* are performing the update of the Spectrum Database according to the information received from the Spectrum LSA. The two types of *LS_Update* refer to the two types of Spectrum LSA format. Once the LSAs are received and the updates are performed, the acknowledgement messages (ACKs) are sent back to the originating nodes.

When the *CheckType* state identifies that a received packet is not a Spectrum LSA but an ACK packet, it sends it to the *LS_ACK* state which is responsible for updating the list of received ACKs. This is done for verifying if ACK messages are received from all neighbors and if this is not the case, retransmission should be taken into account.

RSVP-TE module

The RSVP-TE module is responsible for handling every incoming connection. The module deals with the specific *PATH* and *Resv* messages as well as with the rest of RSVP messages describing different errors in reserving resources. For each connection, an associated child process is created and this will track the progress of the connection from signaling until tearing-off when the resources and the child process are removed.

RSVP-TE module is described by the FSM implementation in Figure 15. The *Init* state performs a mapping between the simulated model links and nodes and the Dijkstra graph (edges and vertices) associated to this node with the purpose of simplifying the process of handling and updating edges and weights. Once the module receives the remote interrupt from the Routing module, the process moves to the *Idle* state. From here, the process uses the *Req_Handle* state for every incoming connection request as well as receiving a *PATH*, *Resv* or an error message. Also, in the *Req_Handle* state, the actual Path computation process is performed which can take into account either the Shortest Path algorithm or the *Relaxation graph* and *Weighted graph* procedures for advanced routing strategies. The *Weighted graph* strategy is performed by always updating the weights for every edge in the Dijkstra graph before performing path computation while the *Relaxation Graph* strategy is done by temporarily enabling or disabling the edges according to the requested slice size.

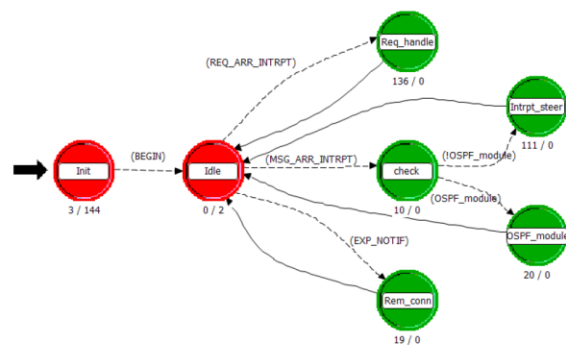


Figure 15: RSVP-TE process model

Whenever a new connection is requested and a new child process is created, the number of required Spectrum Slots (slice size) is computed by taking into account the flex-grid attributes that are associated to this node (e.g. Central Frequency Granularity).

The process also handles the receipt of packets or messages and this is handled by checking the message type in the *check* state. In case it is an OSPF message (LSA or ACK), this is forwarded on the interface towards the OSPF module, otherwise the message is passed to the child process which will consider it depending on the current state of the connection.

The *Rem_conn* state is responsible to release the resource in the case a connection expires. The OSPF child process also contains the implementation of the Spectrum Assignment strategies as well as the particular implementation of the RSVP mechanism with regards to the flex-grid architecture, such as: collecting spectrum slots, verifying that spectrum slots are contiguous, considering only the central frequency and the size of a slice to identify a connection etc.

4.2 Attributes and statistics

In order to make the model and the scenario configuration more flexible, a number of attributes were defined so they can be adjusted according to the user's demand and they are described in Table 2.

Attribute	Possible value
CFG (Central Frequency Granularity)	6.25; 12.5; 25; 50 [GHz]
SSG (Spectrum Slot Granularity)	12.5; 25; 50 [GHz]
OSPF advertising procedure	Inclusive Label Set Bitmap encoding
OSPF routing algorithm	Shortest Path First Shortest Path First on weighted Dijkstra graph
Relaxation graph (strategy)	ON / OFF
Wavelength Assignment	First-Fit, Mixed-Fit, Random Assignment
OSPF Retransmission timer	[integer value]
OSPF MinLSInterval	0, 30, 60, 180 [sec]

Table 2: Network model attributed

Regarding the collected statistics, in this implementation we consider the *blocked connections* which represent the total number of blocked connections in the network and the *network load* which stands for the total number of created LSA advertisement packets in the network.

5. Simulation Results and Analysis

5.1 Signaling scenario

In order to test and evaluate the proposed and implemented extensions for RSVP-TE, we deployed a COST 266 network model as shown in Figure 9.

We evaluate the three different spectrum assignment methods: First-Fit, Random-Assignment and Mixed-Fit. The results in terms of percentage of blocked connections are depicted in Figure 16. It can be observed that First-Fit outperforms the other methods because it packs the spectrum better while minimizing the effects of fragmentation.

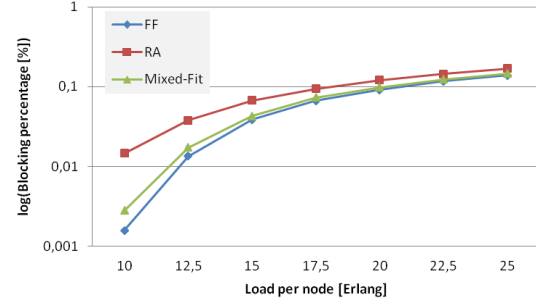


Fig 16: Blocking for different Spectrum Assignment methods

Fragmentation represents an issue for the flex-grid environment because when slices are assigned, there is a possibility that between two assigned neighbor slices there is a gap of free spectrum between them. This scenario can be repeated in a single fiber or link and considering also that those gaps can have small sizes, they cannot handle specific slice requests.

5.2 Routing scenario

For the routing evaluation an NSF network model is deployed as shown in Figure 10. The goal of the implementation is to prove the functionality of the OSPF-TE extensions as well as to emphasize the increased efficiency of the flex-grid architecture based on advanced routing strategies. The results presented further were also submitted and accepted in [8].

The simulation scenario considered different *MinLSInterval* timer value for the LSA updates and verifies the two formats for the LSA Label Set sub-TLV. As shown in Figure 17, if the Inclusive Label Set sub-TLV format is used in the LSA packets, the percentage of the blocked connections is highly dependent on the timer value.

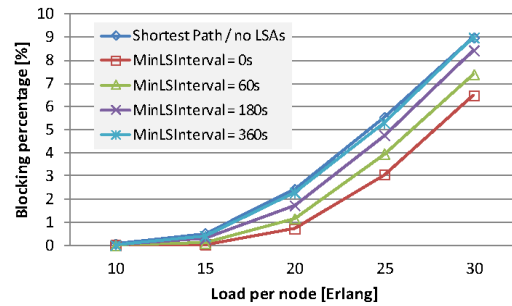


Fig 17: Blocking for different advertising timers in case of using Inclusive sub-TLV format

It can be also observed in Figure 17 that the lowest blocking is achieved for *MinLSInterval* 0 which means that whenever a change in the spectrum is observed on any link connected to that node, an LSA packet is created to advertise that change without waiting for any timer. Moreover, if higher timer values are used (e.g. 360 sec or more), the blocking percentage becomes worse than for the Shortest Path case – which represents the case where no OSPF-TE LSA based information is used for optimizing path computation.

On the other side, in Figure 18 we can observe that when we implement the LSAs using bitmap encoding sub-TLV format, the blocking is less dependent on the *MinLSInterval* timer value. This is because the bitmap encoding sends the whole spectrum information in one fiber and not only the information about specific spectrum slots which get changed as in the previous case. Because of this format, even if the timer value is high, an LSA update covers changes that occurred during the timer period by sending the latest update of the spectrum status in the whole fiber. We can notice in Figure 18 that even for high values of the *MinLSInterval*, the blocking remains at similar low level.

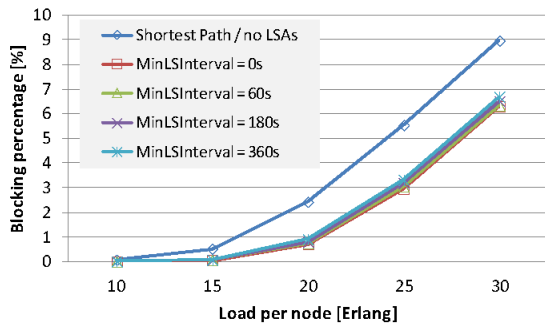


Fig 18: Blocking for different advertising timers in case of using bitmap encoding sub-TLV format

The *MinLSInterval* timer configuration is important because it affects the load that the LSA packets determine on the control plane. At the same time the timer selection is a trade-off between getting up-to-date OSPF-TE LSAs and keeping the control plane load at a reasonable level. As it is shown in Figure 19, if the *MinLSInterval* timer is lower than 180 seconds in this scenario, the control plane load gets very high and unstable. The conclusion is that the bitmap encoding is clearly preferable for advertising flex-grid spectrum slot information in LSA packets.

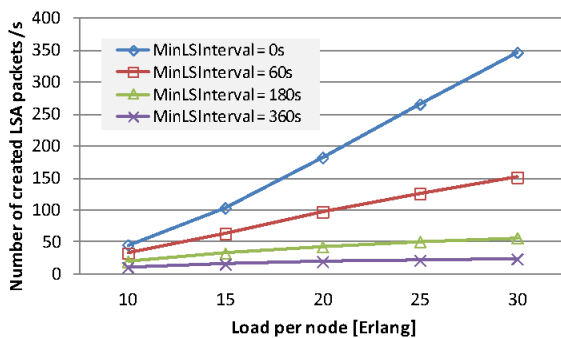


Fig 19: Control plane load due to OSPF-TE overhead

Based on the information gathered from the OSPF-TE LSA advertisements, Spectrum Databases are created containing information about the status of the spectrum on all the links in the network. By using this information in the path computation engine, the source node is able to select an optimal path for the connection, considering the amount of available resources in every link in the network. Figure 20 shows the benefit of using two routing strategies based on the information gathered in the Spectrum Database. In the case of *Relaxation graph* strategy, by only disabling the links that cannot cope with the requested slice, 15% improved blocking can be achieved. In the other case of using *Weighted graph* strategy, up to 70% lower blocking can be achieved for low loaded network (approx. 10 to 30 Erlangs).

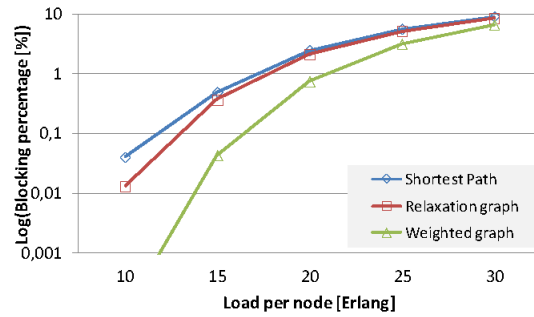


Fig 20: Blocking for advanced routing strategies

Conclusion

The paper presents a novel OPNET Modeler implementation of GMPLS based control plane capable of handling flex-grid elastic optical networks. The model has a flexible design which allows extensions for the OSPF-TE and RSVP-TE not only to support flex-grid but also to enable other flexible parameters specific for elastic optical networks. Throughout this implementation we prove the efficiency of the flex-grid extensions and we enable evaluation for proposed strategies for both routing and signaling aspects.

References

- [1] R. W. Tkach "Scaling optical communications for the next decade and beyond" Bell Labs Technical Journal 14(4), 3-10 2010
- [2] ITU-T G.694.1 Recommendation "Spectral grids for WDM applications: DWDM frequency grid"
- [3] F. Zhang et al., "Framework for GMPLS and PCE Control of Spectrum Switched Optical Networks", IETF draft 2012
- [4] D. King et al., "Generalized labels for the Flexi-Grid in Lambda-Switch-Capable (LSC) Label Switching Routers", IETF draft, 2013
- [5] I. Turus et al., "Evaluation of Distributed Spectrum Allocation Algorithms for GMPLS Elastic Optical Networks", submitted to Globecom 2013
- [6] I. Turus et al., "Evaluation of Strategies for Dynamic Routing Algorithms in Support of Flex-Grid based GMPLS Elastic Optical Networks", ECOC 2013, We.3.E.5
- [7] A. Morea et al., "Efficiency gain from elastic optical networks", Communications and Photonics Conference and Exhibition, 2011

[8] J. Wang et al., "Energy-efficient routing in GMPLS network", OPNETWORK 2011

[9] D. Katz, "Traffic Engineering (TE) Extensions to OSPF Version 2", RFC3630, Sept. 2000

B. Evaluation of strategies for dynamic routing algorithms in support of Flex-Grid based GMPLS elastic optical networks

Evaluation of Strategies for Dynamic Routing Algorithms in Support of Flex-Grid based GMPLS Elastic Optical Networks

Ioan Turus⁽¹⁾, Josva Kleist⁽¹⁾, Anna Manolova Fagertun⁽²⁾, Lars Dittmann⁽²⁾

⁽¹⁾ NORDUnet A/S, DK-2770 Kastrup, Denmark, iotu@nordu.net

⁽²⁾ Department of Photonics Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

Abstract We evaluate OSPF-TE extensions within GMPLS framework in support of flex-grid optical networks. Based on OSPF-TE LSAs, two routing strategies are proposed achieving up to 15% and 70% respectively improved blocking ratio for low loaded network (10-30 Erlangs) compared to the shortest path scenario.

Introduction

Today, the traffic in optical core networks experiences a significant increase due to the development of both advanced access network technologies (e.g. FTTH) and of bandwidth consuming high-end applications (e.g. VoD or HDTV). This presents a resource provisioning challenge to the core optical network.

Current optical network deployments are based on Wavelength Switched Optical Network (WSON) framework meaning that a connection can be associated to an optical channel or wavelength while wavelengths can be switched along the path. 50 GHz grid spacing is defined by ITU-T¹ and it represents a characteristic of the WSON networks. Because of this rigid grid specification, the number of wavelengths that can be assigned per fiber is limited (e.g. about 80 in the C band).

Due to the fact that connections in core networks become more and more heterogeneous, with bitrates varying from 10 to 100 Gb/s, their demand in terms of spectrum resources experiences a significant variation. This aspect cannot be efficiently covered by the ITU-T standard grid and ITU-T defined in the 2nd revision¹ the so called Flex-Grid architecture where the spectrum is sliced with a 6,25 GHz granularity. In this case, for each connection, a certain number of contiguous spectrum slots are chosen forming a slice which can better serve the connection in terms of spectrum utilization.

Flex-Grid networks are one of the enabling technologies for the novel Elastic Optical Network (EO-Net) concept. EO-Net is able to provide elastic optical connections by adjusting symbol-rate, modulation format and Forward Error Correction (FEC) codes while assigning the proper amount of spectrum resources based on flex-grid architecture.

In order to control the Elastic Optical Network, a control plane is required and the current proposed solutions refer either to the Generalized Multi-Protocol Label Switching

(GMPLS) framework or to the OpenFlow based Software Defined Networks (SDN) solution².

This paper presents GMPLS routing based on Open Shortest Path First – Traffic Engineering (OSPF-TE) in EON. OSPF-TE protocol extensions are implemented and new routing strategies are proposed and evaluated with the goal of improving the blocking ratio in the flex-grid environment.

OSPF-TE protocol extensions in support of flex-grid

In GMPLS controlled optical networks, OSPF-TE disseminates information about link/nodes connectivity as well as traffic engineering information such as available or reserved bandwidth. This information is then used by a path computation engine to provide a path for every incoming demand.

Particularly for flex-grid networks, OSPF-TE requires a number of extensions in order to enable the handling of multiple spectrum slots and slices (a slice is formed by a number of contiguous spectrum slots). Before looking into how to extend OSPF-TE capability, an important required element is the generalized label definition³, which allows the control plane to manipulate individual spectrum slots.

There are two different OSPF-TE extensions that we investigate and their goal is to advertise the status of flex-grid channels. The first option is to use the already defined *Available Label Set sub-TLV* (sub-Type Length Value header) from WSON networks with the *Inclusive/Exclusive Label Range* format. This mandates adding a field to carry the state (free or occupied) of the advertised spectrum. Using this extension and adding the sub-TLV to the OSPF-TE Link State Advertisements (LSAs) we can advertise the status of a set of contiguous spectrum slots to the rest of the network by using the start slot, the end slot and the current state of the slice. For the ease of comparison and reference, we will entitle this option as *flex-change sub-TLV*.

The second option is also based on the Available Label Set sub-TLV, but instead, a *bitmap* format is used to show the status for every single spectrum slot defined in a fiber. The bitmap has variable size depending on the Central Frequency Granularity (CFG) which determines the number of existing spectrum slots. For this second case, we will use the name *flex-bitmap sub-TLV*.

For both *flex-change* and *flex-bitmap sub-TLVs* integrated in OSPF-TE LSAs, an important parameter to be taken into account is the *MinLSInterval* timer which defines the minimum time required between the creations of two different LSAs from the same node. The choice of the *MinLSInterval* represents a tradeoff between low control plane load and up-to-date advertisements.

Advanced routing strategies

Based on the information gathered from OSPF-TE LSAs, every node creates its own spectrum database. These databases contain information about the status of all spectrum slots from every fiber/link in the network and this information can be used to develop advanced routing strategies which will allow for improvements in the number of blocked connections. There are two different types of routing strategies we propose and we refer to them as *relaxation graph* and *weighted graph*.

The *relaxation graph* strategy refers to disabling a number of links/edges in the Dijkstra graph (used for path computation) before proceeding to compute the shortest path. The mechanism follows an approach similar with the one where the decision to disable an edge is taken based on the load percentage on the edge⁴. Instead of checking the link loads, we propose a dynamic solution by creating a duplicated graph for every new connection demand where we disable all the edges that do not have at least a number of contiguous spectrum slots equal to the one required by the connection.

The *weighted graph* strategy assigns weights to the Dijkstra graph edges in an efficient way so that incoming demands will prioritize the less loaded edges. By default, the Dijkstra graph has equal weights for all the edges and the chosen path is computed as shortest path first in terms of number of hops. We propose an algorithm for assigning weights which divides the total number of spectrum slots from one fiber in 8 levels. If less than 1/8 of the total number of spectrum slots is occupied, the edge will be assigned weight 1, while if between 1/8 and 2/8

of the fiber is occupied the edge will be assigned weight 2. The assignment will continue in this way with weight values taken from first 8 numbers of the Fibonacci series: 1, 2, 3, 5, 8, 13, 21 and 34. The reason for choosing this series is to get a higher priority for the links that are less occupied and highly decrease the priority for the occupied links.

Evaluation of OSPF-TE flex-grid extensions

The *flex-change* and *flex-bitmap sub-TLVs* are evaluated for their performance in terms of blocking percentage and control plane load. The simulation is based on the NSF network shown in Fig. 1. The implementation of the network as well as the GMPLS OSPF-TE routing engine with extensions is done in the OPNET Modeler simulation tool⁵.

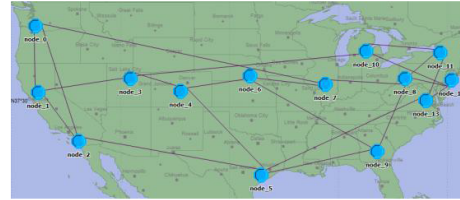


Fig. 1: NSF network in OPNET Modeler.

The traffic is dynamically generated with an inter-arrival time and duration uniformly distributed while the destination is randomly chosen based on a uniform distribution. There are 320 spectrum slots of 6.25 GHz for every link. The connection requests are assigned a number of spectrum slots uniformly distributed between 1 and 16 (equivalent to 6.25 to 100 GHz).

For the *flex-change sub-TLV*, when a connection is established or released only the state of the slots that are changing the state is advertised. Choosing a higher *MinLSInterval* timer implies that a number of spectrum slots changes cannot be advertised which in turn determines out-dated information in the spectrum databases. As shown in Fig. 2, the implementation of *flex-change sub-TLV* determines a blocking ratio that is very dependent on the timer and minimum blocking is obtained when the timer is disabled (i.e., every change is advertised immediately). It can also be observed that for *MinLSInterval* values of 180 s, the blocking is as high as in the case of not using any OSPF-TE information. It must be noted as well that this value is topology dependent.

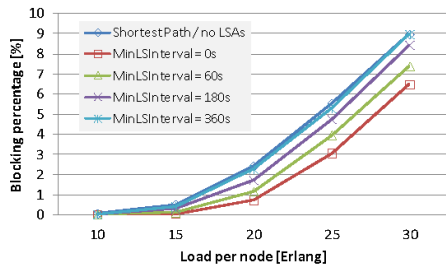


Fig. 2: Blocking percentage for *flex-change* case.

In case of *bitmap-change* sub-TLV, the spectrum database synchronization is expected to be less dependent on the timer because the LSA contain the entire bitmap of the link and even if one change is missed because of the timer, this is covered by the information sent in the very next LSA update. As shown in Fig. 3, the blocking remains at minimum values even for timer values up to 60 or 180 seconds.

Comparing Fig. 2 and Fig. 3, it is observed

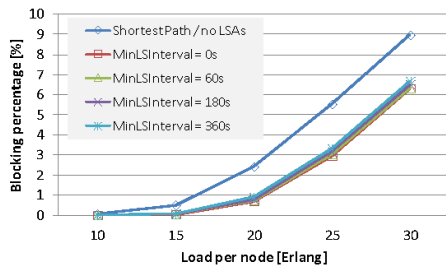


Fig. 3: Blocking percentage for *flex-bitmap* case.

that using *flex-bitmap* sub-TLV based LSAs is less dependent on the timer value than the scenario using *flex-change* based LSAs. This is an important aspect and it is depicted in Fig. 4, where it can be seen that for timer value of 180 s the number of LSAs per second created in the network decreases 6 times, which considerably reduces the load on the control plane. Considering the marginal impact on the blocking percentage it is clear that using bitmap advertisements in OSPF-TE for flex-grid is more efficient.

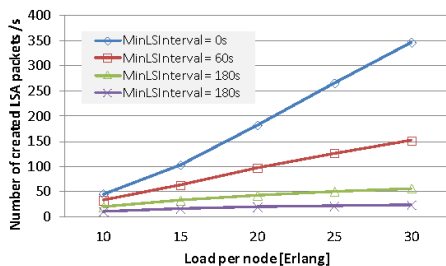


Fig. 4: OSPF-TE overhead for different MinLSInterval timers.

Evaluation of advanced routing strategies

Based on the Spectrum Database information collected by using OSPF-TE *flex-bitmap* sub-TLV advertisements, the *relaxation graph* and *weighted graph* strategies are compared with the case of using default shortest path based path computation. As shown in Fig. 5, the *relaxation graph* strategy is able to decrease the blocking with 67% for a load of 10 E and to 5% for load of 30 E compared to *Shortest Path*. In case of *weighted graph*, the blocking is decreased with 90% for 10 E to 27% for 30 E compared to *Shortest Path*. The simulation shows continued improvements for loads higher than 30E but the percentage decreases to less than 5% and 14% for both methods respectively.

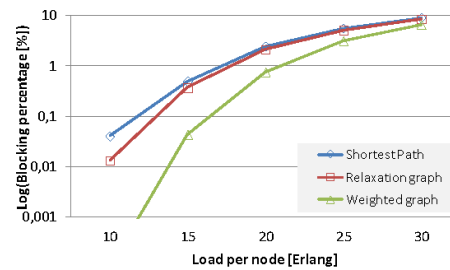


Fig. 5: Routing strategies performance.

Conclusions

In this paper we implemented extensions required for running flex-grid networks in GMPLS routing engine. The bitmap format of the sub-TLV in the OSPF-TE LSAs is shown to be more preferable due to less load on the control plane without compromising the performance significantly.

The two proposed routing strategies emphasize the importance of the spectrum advertisements in flex-grid networks. The *relaxation graph* strategy provides up to 15% lower blocking for less loaded networks (20 E) while the *weighted graph* method is able to provide up to 70% improved blocking.

Acknowledgements

This work is part of the CELTIC Elastic Optical Networks (EO-Net) project (CP07-006).

References

- [1] ITU-T G.694.1 Recomm., *Spectral grids for WDM applications: DWDM frequency grid*.
- [2] L. Liu et al., *IEEE Globecom, Workshop on Flexible Optical Networks*, 352, 2012.
- [3] D. King et al., *Generalized labels for the Flexi-grid in Lambda-Switch-Capable (LSC) Label Switching Routers*, IETF draft, 2013.
- [4] R. Munoz et al., *Proc. OFC'12, Mo2D4*.
- [5] OPNET Technologies, <http://www.opnet.com>

C. Traffic-aware Elastic Optical Networks to leverage Energy Savings

Traffic-aware Elastic Optical Networks to leverage Energy Savings

Ioan Turus, Anna Manolova
Fagertun and Lars Dittmann
Technical University of Denmark
DK-2800, Lyngby, Denmark
iotu@fotonik.dtu.dk

Annalisa Morea
and Dominique Verchere
Optical Networks Department
Bell Labs Centre de Villarsceaux
Nozay, France

Josva Kleist
NORDUnet A/S
DK-2700, Kastrup, Denmark

Abstract— Because of the static nature of the deployed optical networks, large energy wastage is experienced today in production networks such as Telecom networks. With power-adaptive optical interfaces and suitable grooming procedures, we propose the design of more energy efficient transport networks. Optical network re-configurations are performed by GMPLS node controllers according to monitored traffic information. The investigated energy reduction strategies are simulated on two large scale transport networks (DT17 and COST37). The results show that the energy savings obtained by these strategies depend on the variability of the carried traffic and the characteristics of the network topology. For medium-size DT17 network significant (more than 37%) power savings are achieved only with symbol-rate adaptation while less savings are achieved for modulation format adaptation. In case of pan-European COST37 network, for both symbol-rate and modulation format adaptations significant savings are obtained. Mixed adaptation (jointly performing symbol-rate and modulation format adaptations) used together with optical grooming allows up to 44% and 47% power savings in DT17 and COST37 networks respectively, close to the optimum power savings case 48,2% computed when the power follows exactly the traffic demand pattern.

Keywords—energy; efficiency; elastic; GMPLS; grooming;

I. INTRODUCTION

Today, network planning is done on the basis of the peak traffic forecasted during a given timeframe, typically yearly periods. Between 30%-60% is the typical annual growth ratio in core networks according to [1]. Thus, the deployment and activation of opto-electronic (OE) devices is done on a per-season basis according to the traffic increase and also to the operational costs associated to the equipment commissioning.

Moreover, traffic transported in core optical networks presents predictable fluctuations such as daily and weekly variations and thus the estimated transported traffic is higher than the actual traffic present in the network (e.g. a drastic case for DT network with an average of 15% with minimums of 5% and maximums of 100% are experienced [2]).

To minimize costs and guarantee the transport of all forecasted traffic, resource over-provisioning is typically done. The peak traffic does not consider neither the daily nor the weekly traffic fluctuations. Thus, most of activated OE devices are under-exploited, causing large energy wastage [3].

In Fig.1a an example of a weekly traffic variation is illustrated. It can be noticed in data provided by [4] that during the working day traffic fluctuates between 40% and 100%, while during the week-end between 20% and 60%. Fig.1b depicts an example of traffic carried in a network during one-year period, where the growth is between 31% and 59%.

Due to the introduction of elastic optical systems [5], sleep-mode in OE devices [3] and extended capabilities to control planes [6], a core optical network could be capable of adjusting its energy consumption according to the traffic variations.

This study evaluates different energy reduction strategies using power-adaptive interfaces (with on-off capabilities and/or data-rate adaptation) adjusting their power to the transmitted traffic, following predictable fluctuations. Moreover, an optical grooming approach is proposed in order to use the benefits of traffic fluctuations and adaptations of the OE devices. The advanced solutions for power adaptability as well as periodical reconfigurations come at the expense of increased complexity within the control plane. The proposed approach in the present

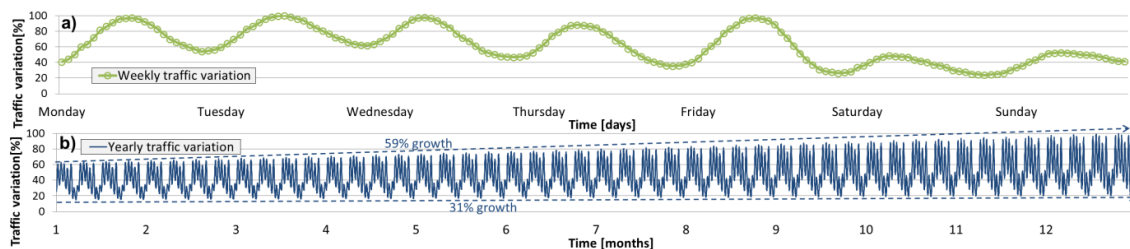


Fig. 1. Average traffic variation per week (green) and per year (blue).

study is to use a distributed GMPLS control plane. New power aware GMPLS control functions are used for triggering dynamic wavelength reconfigurations.

The remainder of this paper is organized as follows: section II details the implemented power adaptive network strategies as well as proposed optical grooming procedure. In section III, the simulated GMPLS control plane functions are described. Section IV presents the simulation setup. Section V provides the results and section VI draws conclusions.

II. POWER ADAPTIVE NETWORK STRATEGIES

Two power-adaptive approaches are studied for adapting the OE energy to the carried traffic: sleep-mode and data-rate adaptation. Hereafter OE devices considered are transponders and regenerators.

Sleep-mode capability relies on the possibility of changing the power state of OE devices. They can be totally or partially powered (up and idle states, respectively) or switched off (down state). When an OE device is in idle state, it can be switched on faster in order to improve network QoS (bandwidth, latency, availability, etc.) for new traffic demands at the expense of low power consumption in idle state with respect to the up state, as in [7].

Data-rate adaptation can be implemented through modulation-format (MF) or symbol-rate (SR) adaptation [8]. MF adaptation may allow power reduction if passing from a more complex format to a simpler one, thus being possible to bypass regenerators, as the optical reach increases with the decrease of the modulation format complexity. Moreover, sleep-mode has to be implemented as well for turning off intermediary regenerators. It has been demonstrated in [8] that with the SR adaptation, the power of an OE device scales down linearly with the reduction of its symbol-rate. However, in case of SR adaptation no regenerator is skipped as the reach is not SR dependent and thus sleep-mode is not necessary for performing SR adaptation [8]. The combination of SR and MF is also proposed, relying on the optimum choice in terms of power consumption between the two adaptations and is called ‘mixed’ in the following.

We propose also to add **grooming** capability when routing a demand. When an optical connection has to be set-up, the policy controller checks if there is an existing optical channel having the same source and destination pair. In case at least

one exists and the sum of the capacity of the existing and incoming connections is lower than 100 Gb/s (channel maximum capacity) during the common lifetime of the two connections, then grooming is feasible and the incoming connection is groomed into the existing one.

If MF or SR adaptation is performed, the channel data-rate is re-configured when the connection capacity changes. In this study, the considered rate-adaptive OE devices can handle: 25, 50, 75 and 100 Gbps, like in [7]. Table I provides the power consumption values of the transponders considered in this work. Regenerators consume twice the energy of the transponders working at the same rate, as they are realized by two transponders back-to-back. When OE devices are idle their consumption is 18W for a transponder and 36W for a regenerator [8]. As in this study we want to emphasize the impact of regenerators in the network power consumption, reach values are reported in Table I, but they are halved compared to values reported in [8]. In Table I the eight possible SR and MF configurations of an OE device for carrying the required data-rate are shown.

III. IMPLEMENTATION OF EXTENDED CONTROL FUNCTIONS

A GMPLS based control architecture is considered. The simulations are performed considering that one RSVP-TE and one OSPF-TE instance run at each node. RSVP-TE controller re-configures the elastic OE devices by changing the parameters (SR and MF) of the wavelength connections. These reconfigurations are possible because the trigger messages [9] carry new objects. The information about new SR and MF attributes is encapsulated into an RMSA Explicit Route (ERO) sub-object using dedicated TLVs as proposed in [6]. Compared to [6], SR information is added to the RMSA sub-object within a dedicated TLV. The implemented OSPF-TE controller is responsible to perform network topology advertisements without any traffic-engineering information.

The traffic aware policy function at every controller node monitors the variation of the bit-rate and only when required, it triggers new connections; also it verifies the possibility of grooming the traffic of established connections. For the mixed adaptation scenario, the policy function of the node controller decides also which data-rate adaptation is the most power efficient. When an adaptation or grooming is decided, the RSVP-TE controller proceeds with the required signaling to implement the reconfiguration. The policy function runs also a timer which enforces the minimum time interval between two consecutive re-configurations of the connection data-rates.

For data-rate adaptation scenarios, the controller operates modifications on the connection capacity. The SR adaptation only entails a rate modification which has to be notified to all OE devices along the LSP (Label-Switched Path). Concerning MF adaptation, as the optical reach depends on the adopted modulation format, and if the LSP length is longer (shorter) than the optical reach related to the modulation format, hence one or more regenerators have to be released (set-up respectively). The required regenerator status along the LSP is transported in RSVP-TE messages by using a Regenerator Object (RO), as proposed in [10], to indicate at every node the activation/deactivation of a regenerator. When a node receives

Table I: Transponders power consumption as a function of symbol-rate (SR) and modulation format (MF).

Payload (Gbps)	SR (Gbd)	MF	Reach (km)	Power (W)
100	28	PDM-QPSK	600	350
	75	PS-QPSK	900	350
50	21	PDM-QPSK	600	255
	28	PDM-BPSK	1250	350
25	14	PDM-QPSK	600	206
	28	SP-BPSK	1500	350
	14	PDM-BPSK	1250	206
	7	PDM-QPSK	600	189

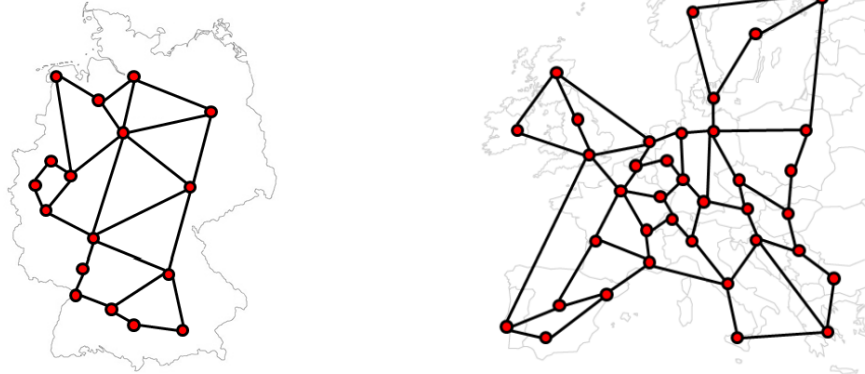


Fig. 2. DT17 network [11] (left) and COST37 Pan-european network [12] (right).

the Regenerator Object which assigns a regenerator to its own node id, then a regenerator is reserved, activated and linked to the connection id of the current advertised connection.

The decision about reconfiguration of the connections is always initiated by the source node. Whenever a re-configuration is possible, a trigger signaling process is initiated. A PATH message transports the new MF and/or SR configuration into dedicated sub-objects. The RESV message confirms the reservation of OE devices, and the MF and/or SR configuration. Whenever new OE devices are reserved (RESV message received) they switch from off to on state and vice versa when they are released.

IV. SIMULATION IMPLEMENTATION

To estimate the energy savings provided when traffic over-provisioning is considered, we dimension two different network topologies, a national coverage network DT17 and a pan-European network COST37, as described in Table II.

Traffic is generated in all nodes, connections are uniformly distributed and their peak capacity can be 50, 75 and 100 Gbps. The traffic demands are requested with an exponentially distributed mean inter-arrival time of 2 hours and hold on with an exponential distribution of a mean value of 40 hours, providing a load per node of 20 Erlang. Every link carries up to 80 wavelengths and no blocking is experienced.

The traffic taken into consideration follows a weekly variation as derived from statistics in [4]. In average there are 410 and 837 connections active at a given time in the DT17 and COST37 networks respectively. Considering the fact that the number of connections is constant during the year, the growth in transported traffic is given by the growth within each connection data-rate. Thus, between week 1 and week 52, for

Table II: DT17 and COST37 network topologies characteristics [11], [12].

	DT17	COST37
Number of nodes	17	37
Number of links	26	57
Mean Link Length [km]	170	648
Min Link Length [km]	36	218
Max Link Length [km]	353	1977

DT17 the traffic varies from 13.4 Tb/s to 18.4 Tb/s while for COST37 network the transported traffic varies from 27.4 Tb/s to 37.6 Tb/s, resulting a transported traffic growth of 37.3%.

The baseline scenario sets-up all connections at 100 Gbps, regardless of their actual requested capacity (always ≤ 100 Gb/s). When a connection is released, OE devices are turned off. To dimension the network, the peak-capacity is considered and necessary OE devices are deployed. The number of requested OE devices is independent of the chosen power-adaptation strategy. In Table III, the average number of transponders and regenerators which have to be installed in every node for enabling a zero blocking is given.

The following energy savings strategies are compared:

- *On/Off* scenario (baseline scenario): only sleep-mode is used and all connections are set-up to 100 Gbps; the minimum amount of required regenerators is configured along the path to support the 100 Gbps connection based on a heuristic algorithm (i.e. it assigns a regenerator to every node when the distance between two consecutive regeneration hops is longer than the maximum reach of the selected MF). As traffic is dynamic, the static power management is not considered and this strategy is used for the comparison with the other energy efficient strategies.
- *MF* scenario: modulation-format adaptation is performed together with sleep-mode strategy; the less complex modulation format capable to carry the incoming traffic is chosen and only used regenerators are powered on.
- *SR* scenario: symbol-rate adaptation is performed without sleep-mode. Required regenerators are the same as for 100Gb/s connections, but their power is proportional to the used symbol-rate, which adapts to traffic variations.
- *Mixed* scenario: combines MF and SR and always chooses their combination providing the minimum power consumption for the considered path and required data-rate.

Table III: Average number of OE devices per node.

	DT17	COST37
Transponders per node	48	48
Regenerators per node	16	97

- On/Off, MF, SR and Mixed *with grooming* – all previous strategies used together with grooming algorithm (detailed cf. Section II).

Simulations run for a one-year period. A number of 10 different random distributions of traffic are drawn with the purpose of minimizing, through averaging, the influence of specific random traffic patterns on the overall results.

V. RESULTS

A. Power consumption for different energy savings strategies

Fig.3a shows the average power consumption along the year for the DT17 network topology taking into consideration four scenarios: On/Off only, MF, SR, Mixed and Mixed together with grooming enabled. The small fluctuations for On/Off case are due to the random set-up of connections. Also, for the On/Off scenario, the increase of the energy consumption during the year is almost imperceptible because all connections are set-up at 100 Gbps. For the rate-adaptive scenarios, the effect of the traffic growth is visible because for the MF scenario more regenerators are set-up (due to the use of more complex MF, see Fig.4a, whereas for the SR adaptation, higher and more energy hungry SR is used. For both MF and SR scenarios we observe that the energy consumption follows the traffic variations presented in Fig.1b. Concerning MF, we observe that its average power consumption does not follow daily variations during the first half-year period and afterwards peaks appear and correspond to peak traffic. This is due to an

increase in the number of needed and powered on regenerators when peak traffic overpasses OE devices data-rate levels.

Fig.3b zooms on the average power variation of week 42 for DT17 network scenario. It can be observed that power is relatively constant for On/Off strategy, which is expected since this does not involve any adaptation to fluctuations. Moreover, SR and Mixed adaptations are able to significantly adapt the power consumption to day/night and weekend fluctuations with Mixed adaptation achieving the lowest power consumption. MF adaptation follows as well traffic fluctuations and provides reduced power consumption but significantly higher than SR and Mixed scenarios since the low number of regenerators deployed in the network does not permit significant adaptations based on the regenerators' sleep-mode capability.

Fig.3c shows the power consumption for the COST37 network scenario. Results are similar with the ones in Fig.3a as the power consumption for On/Off scenario is relatively constant but the average power is approximately 6 times higher than in case of DT17 network, despite the fact that COST37 network only has 2.1 times more nodes and links. The reason why power consumption grows 6 times is given by the average length of the links which is 3.8 times higher for COST37 compared to DT17 as well as by the number of nodes which is 2.1 times higher for COST37. Thus, the longer links demand for a higher number of regenerators while the higher number of nodes determines a higher number of transponders (since the number of connections generated in every node is

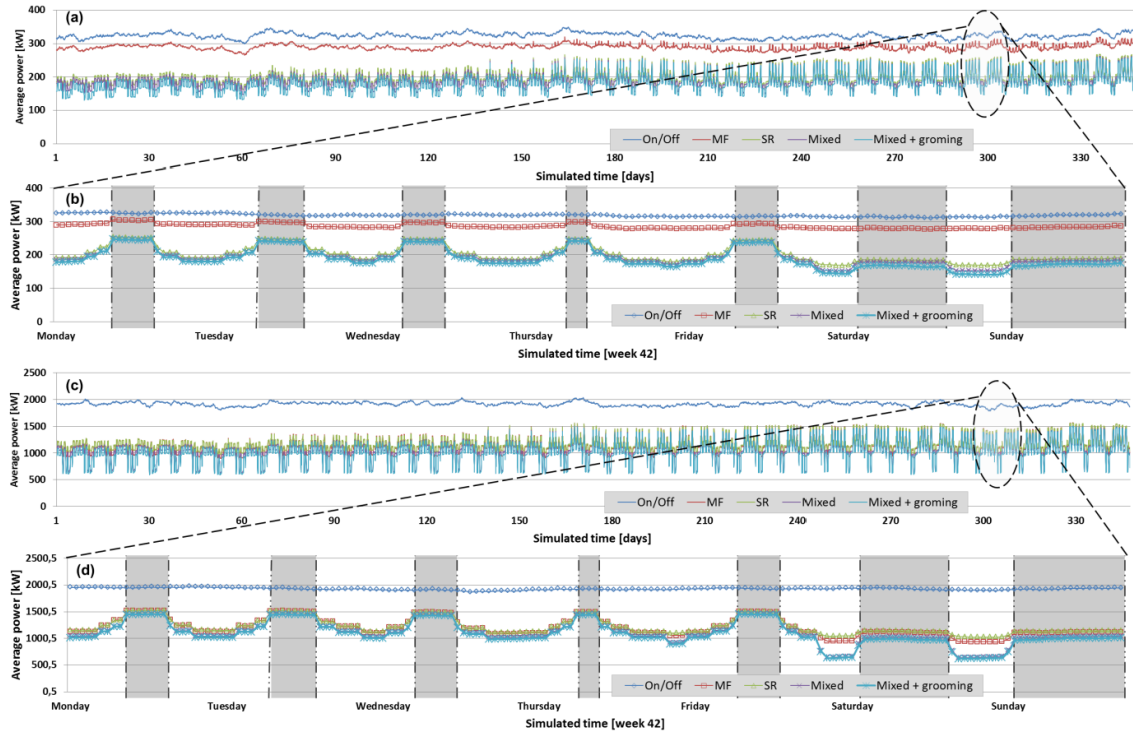


Fig. 3. Average power variation per year for DT17 (a) and COST37 (c) and average power per week for DT17 (b) and COST37 (d) network scenarios.

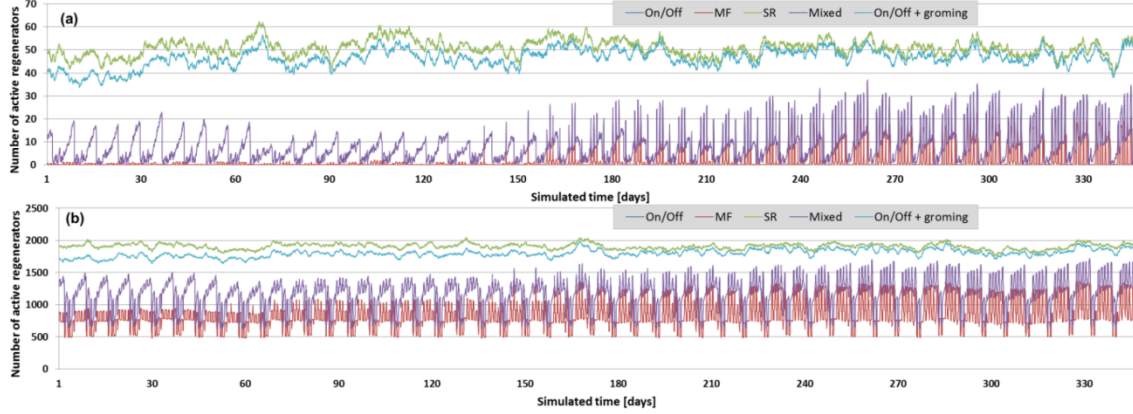


Fig. 4. Number of active regenerators for DT17 and COST37 network scenarios.

constant). Moreover, Fig.3c shows that the power associated to MF scenario is not any longer relatively flat during the first half of the year as for DT17 network in Fig.3a. For COST37 network, due to the long length of the links the number of regenerators is very well adapted to the traffic fluctuations and determines a power consumption which varies with similar fluctuations as the input traffic (Fig.4b). In case of SR and Mixed adaptations results are similar, from the variation trend point of view, with the ones obtained for DT17 network.

In Fig.3d a zoom over power consumption in week 42 for COST37 network is provided. When comparing results in Fig.3b and Fig.3d it can be observed that MF, SR and Mixed adaptation (w/o grooming) achieve similar power consumption while a significant difference is given for the night periods of the weekends where Mixed adaptation achieves a significantly lower power consumption compared to MF or SR adaptations. Another consequence of the high number of OE devices (i.e. they allow for a better power adaptation which translates into higher power reductions) is emphasized by power fluctuations in Fig.3b and Fig.3d. Hence, for SR and Mixed scenarios the power fluctuations amplitude is significantly higher in the COST37 network where the power consumption varies from 700 kW to 1500 kW during week 42 (53% variation) than in DT17 network where variation is from 160 kW to 250 kW (36% variation).

Fig.4 depicts the number of active regenerators in DT17 and COST37 network topologies during the year for On/Off, SR, MF, Mixed and On/Off with grooming scenarios. It can be observed that for both networks, the number of active regenerators in On/Off and SR scenarios is the same (overlapped graphs) since both configure the connections with a number of regenerators equivalent to 100 Gbps connections. The difference however, in terms of consumed energy is high (as seen in Fig.3) due to the possibility of tuning symbol-rate for SR scenario. Moreover, when comparing the two topologies, we observe that in DT17 network for MF scenario the number of regenerators is almost zero during the first half of the year; so mainly the transponders contribute to power adaptation for DT17 network. In case of COST37, due to the presence of high number of active regenerators, they are well

adapted according to the traffic fluctuations. In case of Mixed scenario, for both networks the number of active regenerators is slightly higher compared to the MF scenario and this is due to cases when energy is reduced by reducing the symbol-rate instead of reducing the number of active regenerators. Fig.4 emphasizes as well the case of grooming applied to the baseline (On/Off) scenario and the conclusion is that when grooming is enabled, a lower number of regenerators is required (since grooming determines fewer active connections, due to grooming). However, towards the end of the year the difference in the number of regenerators between On/Off with and without grooming becomes close to 0 since the data-rate fluctuations grow within every connection, making it less likely for two connections to be groomed without exceeding the maximum available capacity per connection of 100 Gbps.

B. Power savings and energy efficiency

Fig.5 shows the relative difference between the average and the peak traffic over diverse time periods: daily, weekly, and yearly. Thus, if the input traffic model only considers daily variations, ideally 23.4% energy savings could be achieved if the power adaptation perfectly follows the traffic variation along the year. Moreover, if the weekly variations are accounted in the traffic profile, 11.9% yearly energy savings are assessed. If the yearly traffic growth is accounted as well, up to 48% savings can be reached; such values strongly depend on the considered traffic profiles.

Fig.6 shows the power savings for the diverse power-adaptive strategies deployed in the two network topologies. We notice that in all four cases (without optical grooming), the

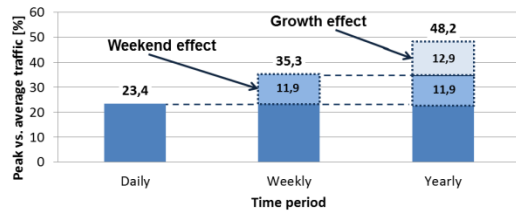


Fig. 5. The normalized difference of average and peak traffic.

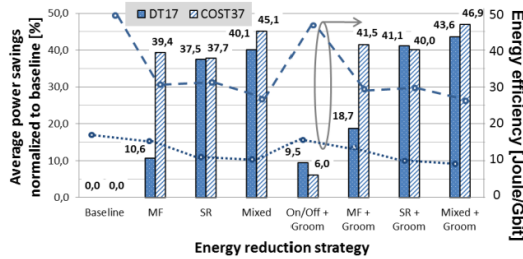


Fig. 6. Power savings and energy efficiency for DT17 and COST37.

energy savings corresponding to COST37 network are higher and this is due to the considerable variation in number of regenerators for COST37 with respect to DT17. Moreover, for DT17 network SR provides higher savings compared to MF adaptation (37.5% and 10.6% respectively); about COST37 network, energy efficiency changes: 39.4% savings for MF adaptation and 37.7% for SR adaptation. When allowing a mixed rate adaptation 5% higher savings are achieved for COST37 network (40.1% for DT17 and 45.1% for COST37).

The grooming approach without rate adaptation has a different efficiency for the two network topologies and it allows for 9.5% and 6% savings for the DT17 and COST37 scenarios respectively. This is explained by the fact that in the COST37 network there are more (36 compared to 16) possible destinations for a connection generated in one node, hence lower probability of having a different connection between the same source-destination nodes. Thus, while having the same load per node (same number of connections generated in one node), it is more difficult to find a connection with same source/destination pair for DT17 which allows grooming for a new incoming connection (cf. to the grooming algorithm in Section II). Thereby, when grooming is combined with the MF, SR and Mixed adaptations SR yields higher savings for DT17 compared to COST37. Generally, we observe that the proposed grooming algorithm improves the energy efficiency in networks having a limited number of nodes.

The advantage of performing only SR adaptation with grooming is the lower complexity of the control plane and the signaling process, because there is no need for regenerator set-up/release due to MF adaptation. Higher savings are reported for mixed and grooming strategies. For DT17 network they are 43.6% and 46.9% for COST37.

In terms of energy efficiency, for DT17 network the energy efficiency can be decreased from 17 J/Gbit in baseline scenario to 9.6 J/Gbit in Mixed with grooming scenario, while for COST37 network the energy efficiency decreases from 49.8 J/Gbit to 26.4 J/Gbit for the same scenarios.

VI. CONCLUSIONS

Exploiting the over-provisioning of optical resources as well as the yearly traffic variation and traffic growth offers a good opportunity for reducing the overall energy consumption in a core optical network. A proposed traffic-aware GMPLS-based control plane with dedicated RSVP-TE protocol extensions allows for dynamic reconfiguration of the optical channels according to the traffic fluctuations.

Strategies based on sleep-mode, data-rate adaptation and grooming allow for reductions of up to 43.6% and 46.9% of the total energy consumption for DT17 and COST37 network scenarios, respectively. When MF adaptation is applied, the efficiency in terms of energy savings is strongly related to the size of the network and the length of the average path – thus, larger the network is with respect to the optical reach, the more efficient MF adaptation is, because of larger variations on the number of regenerators.

Moreover, the grooming approach improves the energy efficiency depending on the network topology: higher energy savings are possible for smaller network topologies at a similar load. Despite the fact that Mixed adaptation and grooming allow for highest energy savings in both network scenarios, a simplified network management can be performed at the expense of slightly lower energy savings. Thus, for DT17 network, running SR adaptation with grooming allows to skip sleep-mode features at the expense of 2.5% lower energy savings (compared to the best case, where Mixed adaptation and optical grooming is deployed). In case of COST37 network, deploying a mixed adaptation approach without grooming allows for a simplified policy controller at the expense of 1.8% lower energy savings.

ACKNOWLEDGMENT

The work in this paper was supported by FP7 IDEALIST and Celtic Plus SASER projects and GreenTouch consortium.

REFERENCES

- [1] C. Lange, "Operator perspective on broadband network traffic evolution," in Proc. European Conference on Optical Communications, Amsterdam, Netherlands, Sep. 2012, paper Mo.2.D.1.
- [2] R. Husermann et al., "Analysis of the energy efficiency in IP over WDM networks with load-adaptive operation," in Proc. ITG Conference on Photonic Networks, Leipzig, Germany, May 2011, paper 31.
- [3] A. Morea et al., "Traffic variation-aware networking for energy efficient optical communications," in Proc. Optical Network Design and Modeling, Brest, France, April 2013, pp. 29-34.
- [4] NORDUnet traffic with Customers – Average In traffic for Week 23 2014, <http://stats.nordu.net>.
- [5] O. Gerstel et al., "Elastic optical networking: a new dawn for the optical layer?," Commun. Mag., IEEE, vol. 50, no. 2, pp. S12-S20, Feb. 2012.
- [6] R. Casellas et al., "Design and experimental validation of a GMPLS/PCE control plane for elastic CO-OFDM optical networks," IEEE J. Sel. Areas Commun., vol. 31, no. 1, pp. 49-61, Jan. 2013.
- [7] A. Morea et al., "Power management of optoelectronic interfaces for dynamic optical networks," in Proc. European Conference on Optical Communications, Geneva, Switzerland, Sep. 2011, paper We.8.K.3.
- [8] A. Morea et al., "Data rate adaptation for night-time energy savings in core networks," J. Lightw. Technol., vol. 31, no. 5, pp. 779-785, 2013.
- [9] AL. Berger et al., "RSVP Refresh Reduction Extensions," IETF RFC 2961, April 2001; www.rfc-editor.org/rfc/rfc2961.txt.
- [10] F. Cugini et al., "GMPLS extensions to encompass shared regenerators in transparent optical networks," in Proc. European Conference on Optical Communications, Berlin, Germany, Sep. 2007, paper 9.5.4.
- [11] R. Husermann et al., "A set of typical transport network scenarios for network modelling," in ITG-Conference Photonic Networks, Leipzig, Germany, May 2004, pp. 65-71.
- [12] M. Christian et al., "Pan-European optical transport networks: An availability-based comparison," Photonic Netw. Commun., vol. 5, no. 3, pp. 203-225, May 2003.

D. Energy savings in dynamic and resilient optical networks based on traffic-aware strategies

Energy savings in dynamic and resilient optical networks based on traffic-aware strategies

Ioan Turus, Anna Manolova
Fagertun and Lars Dittmann
Technical University of Denmark
DK-2800, Lyngby, Denmark
iotu@fotonik.dtu.dk

Annalisa Morea
and Dominique Verchere
Optical Networks Department
Bell Labs Centre de Villarcoux
Nozay, France

Josva Kleist
NORDUnet A/S
DK-2700, Kastrup, Denmark

Abstract— An analysis of the energy savings is presented when taking into account a complete traffic model for a one-year time period. Daily and weekly traffic fluctuations as well as yearly traffic growth are considered when analyzing the power consumption. Low power mode in optoelectronic devices (sleep-mode and rate adaptive capabilities) is implemented within a traffic-aware networking approach. The impact of dedicated 1:1 protection in a dynamic network scenario is considered and a comparison is made with the unprotected case. A GMPLS control plane is implemented and used to re-configure the power-adaptive devices and connections. Results show that symbol-rate adaptation provides high savings for unprotected scenarios (37% energy savings w.r.t. unprotected Baseline), while for the protected scenarios better results are obtained for modulation format adaptation which includes sleep-mode (57.1% energy savings w.r.t. protected Baseline). Moreover, compared to the Baseline scenarios the Mixed adaptation, combining both symbol-rate and modulation format, is the most power-efficient strategy providing 39% energy savings for unprotected scenario and 70% energy savings for dedicated protection scenario.

Keywords—energy; efficiency; elastic; GMPLS; protection;

I. INTRODUCTION

Today, core optical networks experience a significant increase in traffic given by the introduction of novel access technologies such as FTTH, novel mobile networks technologies, as well as the development of new and demanding applications such as HDTV and online gaming. Moreover the number of users is continuously increasing and overall network traffic increase is estimated to be about 30%-60% per year [1]. A consequence of this traffic growth is the ever increasing amount of resources and their capacity for carrying it, yielding an uncontrollable rise of the consumed energy. Moreover, when traffic recovery has to be ensured (by dedicated or shared protection [2]), even more resources have to be deployed, with a consequent impact on the whole energy consumed by the network [3]. The estimated overall traffic increase is described by a CAGR (Compound Annual Growth Rate) of 42.6% according to [4] which will produce a growth in the energy consumption of the overall network of 10.4% CAGR according to [5]. Hence, it becomes imperative to find more energy efficient solutions both by developing a traffic-aware networking approach and by controlling the operational modes thus improving the energy efficiency.

In this work we propose an operational approach allowing energy savings associated to the monitored traffic transported in the network. We observed that both traffic growth assumptions and recovery strategies are based on the assumed peak traffic. However, in reality the traffic transported in a network presents predictable variations, such as diurnal and weekend related. Hence the estimation of the transported traffic, based on week-peaks, is higher than the average that is actually transported (e.g. for Orange network [6], an average of 61% traffic is observed while variation is between a minimum of 14% and a maximum of 100%; a worse case is given in DT network [7], where the traffic average is 15% while minimum and maximum variations are 5% and 100% respectively).

We denote as over-provisioning the amount of deployed and powered resources that are not used all the time because of traffic variations (fluctuations and growth) and recovery strategies, and we assess the power efficiency of the network when energy over-provisioning is minimized.

To control the unsustainable energy consumption of the network linked to the traffic increase, a solution can be provided by the introduction of elastic optical devices [8], where the connection capacity can be adapted to the actually carried traffic. In an elastic network, opto-electronic devices (OEs), i.e. transponders and regenerators, can be tuned to a proper configuration in terms of symbol-rate and/or modulation format, so that the energy consumption of the network is proportional to the traffic demand and the total consumed energy is reduced [6]. In [6] only the impact of daily variations is considered and the impact of incoming demands is not accounted. Besides elastic networking, strategies switching off completely or partially OE-devices are proposed [9]. These methods, named sleep-mode in the following, optimize the number of fully powered-on devices resulting in improving the overall energy efficiency of the network. The elastic system capabilities of the network together with sleep-mode strategies, jointly with the introduction of extended capabilities to control planes [10] allow an optical network to adjust its energy consumption in relation with the actual demanded traffic. In [11] a comparison of the energy efficiency improvement given by the introduction of elastic networks and sleep-mode is proposed when diurnal variations are accounted. In [12] the interest of using elastic networks is presented when IP protection is performed and diurnal variations are taken into

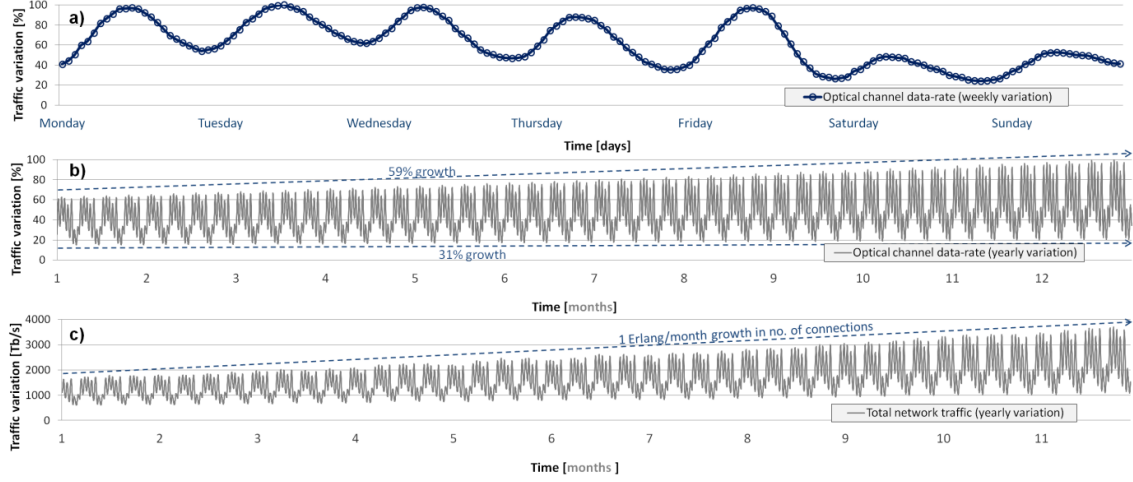


Fig. 1. Traffic variation of an optical channel in one week (a) and one year (b) and total network traffic variation in one year (c).

account. However, a complete study of the impact of the different over-provisioning factors (i.e. traffic growth within the data-rate of an optical connection, increasing number of connections, diurnal and weekend fluctuations) including a comparison of the diverse energy efficient strategies is not provided.

This study focuses on a detailed network traffic model which considers both diurnal and weekly traffic variations, as well as yearly increase in terms of both number of connections and their capacity. Moreover, this study defines the impact of the resiliency, provided by a dedicated 1:1 protection scheme. The savings provided by sleep-mode and elastic approaches jointly and separately are assessed.

The remainder of this paper is organized as follows: Section II details the proposed traffic model which naturally describes current core optical networks traffic trends. In Section III, the traffic-aware networking approach based on different energy reduction strategies is described. Section IV presents an example of control plane implementation based on GMPLS and required extensions. In Section V the simulation setup is presented. Sections VI and VII provide the results and conclude the paper respectively.

II. PROPOSED TRAFFIC MODEL

The proposed network traffic model, depicted in Fig. 1, includes two main traffic dynamics as follows:

- Predictable fluctuations, derived from observations in [13]:
 - a) Diurnal variations – during night time, the channel data-rate fluctuates between 100% and 60% (Fig. 1a).
 - b) Weekly variations – during week days the traffic reaches 90% to 100% while during weekend days the traffic reaches maximum 50% to 60% (Fig. 1a).
- Yearly traffic growth, divided into:

c) Optical channel data-rate growth – the considered channel data-rate peak and minimum values experience a growth of 59% and 31% respectively in one year (Fig. 1b).

d) Number of connections – increasing number of connections generated by every node as shown in Fig. 1c.

When the two implemented sources of yearly traffic growth are combined, it results in a total growth of 76% in one year: 38% are given by the growth of the channel data-rate and 38% are given by the increase in number of connections.

An important aspect in a core optical network of a telecom operator is to ensure the reliability of the network and the protection against possible failures. This is another source of increased number of connections to be set-up in the network. There are different strategies proposed for ensuring resilience. In this study dedicated 1:1 edge-disjoint protection is implemented. A policy controller acts in every node in the network when a new optical channel has to be established. The protection span is given by a shortest-path edge-disjoint algorithm. The protection channel is set-up with the same symbol-rate and modulation format as the working connection. The result is that when dedicated protection mechanism is used, a double number of connections are demanded in the network compared to the case when protection is disabled. Also, the number of required OE devices is more than double because protection spans are not following the shortest paths between source and destination, and often they require more regenerators.

Requests connecting two nodes randomly arrive in the source node with an average value described by the mean inter-arrival time and have on average a duration given by the holding time (simulation details provided in Section V).

III. TRAFFIC-AWARE NETWORKING

Considering the continuous traffic growth which faces the static and over-provisioned power and network resources, the need to adapt the energy consumption to the traffic behavior

becomes essential. The way to cope with this challenge is to develop traffic-aware networking strategies. There are two energy reduction strategies defining the traffic-aware approach that we consider for achieving energy savings:

Sleep-mode – an OE device can be partially turned off, i.e. idle state, as it consumes a low amount of power compared to the operational state and it is able to switch back to operational state very fast [9] when a new connection is requested, thus energy savings are provided. Also, an OE device can be powered off, i.e. down state, and in this case it does not consume power but it can be quickly switched on.

Data-rate adaptation – takes into account the advantages of the elastic optical networks architecture where modulation format (MF) and symbol-rate (SR) adaptations can be performed jointly or separately. An OE device tunes between different data-rates (in the considered case the available data-rates are 25, 50, 75 and 100 Gbps). The MF adaptation enables the change of the modulation format according to the traffic variation. When traffic decreases, a less complex modulation can be configured on the corresponding transponders. This results in a longer reach for the optical channel and thus it requires fewer regenerators along the path. Changing the MF does not change the energy consumption of the device, hence to do it the MF has to be combined with sleep-mode approach, so that the energy consumption of the path can be reduced by switching off or by using the idle state for the unnecessary regenerators. When SR adaptation is used, a lower SR can be configured on all OE devices along the path in case the traffic capacity decreases. Moreover, it has been shown in [6] that the power consumption of an OE device is directly related to the operated symbol-rate. Thereby, SR adaptation enables power savings by reducing the symbol-rate of the OE devices. As the transparent reach remains independent from the SR, no regenerator is bypassed and no sleep-mode is required. A combination of the MF and SR modulation formats can be implemented to achieve even higher energy savings [11].

In Table I, the power consumption and the reach of the transponders is provided according to their SR and MF, respectively [6]. Regenerators power consumption is equal twice the consumption of a transponder because they are realized with two transponders in back-to-back configuration. In case of idle devices consumption, a transponder consumes 18W while a regenerator consumes 36W whatever the SR and MF configurations are [9].

TABLE I. TRANSPONDERS POWER AS A FUNCTION OF SYMBOL-RATE (SR) AND MODULATION FORMAT (MF).

Payload (Gbps)	SR (GBd)	MF	Reach (km)	Power (W)
100	28	PDM-QPSK	600	350
	21	PDM-QPSK	600	255
50	28	PDM-BPSK	1250	350
	14	PDM-QPSK	600	206
25	28	SP-BPSK	1500	350
	14	PDM-BPSK	1250	206
	7	PDM-QPSK	600	189

IV. GMPLS CONTROL PLANE

A GMPLS-based control plane is proposed in order to control and configure the analyzed network. RSVP-TE is responsible to set-up and tear-down connections as well as to reconfigure the power state (SR and MF configuration) of an optical channel. Protocol extensions are used to encapsulate the required elastic parameters and Trigger messages [14] were extended for performing the required re-configurations [9].

The actions taken by the GMPLS control plane are provided as a result of computations performed in a policy controller. When adaptation and/or recovery are requested, the necessary information is passed to the GMPLS control plane which performs the required signaling.

Re-configuration of the existing optical channels may be required in data-rate adaptation scenarios. Thereby, when a SR adaptation is performed, a new symbol-rate value has to be advertised starting from the source node to all active OE devices associated to this channel (regenerators and add/drop transponders). When a MF adaptation is performed, the controller in the source node computes another set of regenerator placement along the path, depending on the reach of the chosen modulation format. Afterwards, sleep-mode strategy is applied for the required regenerators and no change on add/drop transponders is operated. When sleep-mode strategy is applied, an OE device can be either in operational state (full powered) or be set to idle or off state.

The information about new SR and MF attributes is encapsulated into newly defined RSA Explicit Route (ERO) sub-object using dedicated TLVs (Type Length Value) as proposed in [10]. A PATH message transports the new MF and/or the new SR information from source to destination while a Resv message confirms the reservation and/or the new physical configuration of the OE devices.

V. SIMULATION IMPLEMENTATION

A German-17 node network, Fig. 2, is used as reference topology for studying the proposed scenarios. Traffic is generated in all nodes and wavelength connections are uniformly distributed between source/destination pairs. The peak capacity of the connections can be 50, 75 or 100 Gbps with an equal probability. Demands are requested with a mean inter-arrival time of 1.6 hours. The holding times are larger with every month which determines the increase in the number

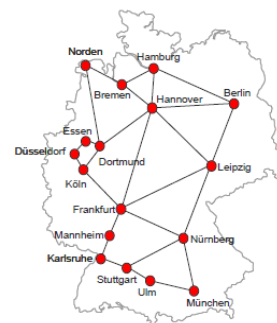


Fig. 2. German 17 nodes network [15].

of connections. Thus, the holding time is given by an exponential distribution of mean varying from 20 to 38 hours – providing a load per node varying from 13 to 24 Erlangs in 12 months period. Every link carries up to 80 wavelengths and the total input traffic in the year does not experience blocking (no lambda congestion).

The considered traffic follows a weekly variation as described in Fig. 1; it experiences a growth in one year of 72% starting from an average traffic of 50 Tb/s in the first week and reaching 86 Tb/s in the last week of the year.

Considering that in a dynamic network scenario, the deployment of the connections follows a random distribution for choosing the source-destination pairs as well as the connection capacity, a number of ten different random distributions are chosen and averaged with the purpose of minimizing the effects given by particular traffic patterns. Moreover, when randomly requesting connection demands, out of the total possible number of source and destination pairs, approx. 20% of the connection pairs are avoided (the 20% value is related to topology characteristics, given in Fig. 2). These connections are the ones which cannot have an edge-disjoint path associated. The links of an already established connection are disabled and the graph is modified so as to compute its edge disjoint protection path; if no path can be computed in the so modified graph, hence it is impossible to establish a protection path for that connection. The reason of discarded connections that do not have edge disjoint protection is to have a fair distribution of connections when we compare protected and unprotected scenarios.

A. The power savings in dynamic unprotected network

- Scenario 1 (Baseline): Only On/Off strategies are applied and all connections are set-up at 100 Gbps configuration.
- Scenarios 2, 3, and 4 correspond to the On/Off strategy together with MF, SR and Mixed adaptation respectively.

B. The power savings in dynamic protected network

- Scenario 1 (Baseline): On/Off strategy is applied in the network for both operational and protection spans.
- Scenario 2: On/Off strategy is applied for working spans. About protection spans, the required regenerators

(associated to 100Gbps configuration) and A/D transponders are only reserved and set to idle state.

- Scenario 3: On/Off strategy is applied together with MF adaptation for working spans. Protection spans are configured as in Scenario 2.
- Scenario 4: On/Off strategy is applied together with SR adaptation for working spans. The protection spans are set-up for a minimum SR configuration (25 Gbps) with OE devices in operational state.
- Scenario 5: On/Off strategy is applied together with Mixed (MF+SR) adaptation for working spans. Protection spans are configured as in Scenario 2.

VI. RESULTS

A. Power savings in dynamic unprotected network

It can be seen in Fig. 3 (top), that the energy consumed during the one year simulated time is growing from an average of around 200 kW to an average of 350 kW. This growth is given by the increase in number of connection – from 13 to 24 Erlangs in one year.

When applying MF adaptation (red curve in Fig. 3) one observes that the average power is significantly reduced and has a similar growth compared to the Baseline (On/Off) case; moreover it starts to slightly follow the daily/weekly trend from the channel capacity fluctuations shown in Fig. 1. These fluctuations are given exclusively by the growth within channel's bit-rate. It can be seen in Fig. 3, that from around day 150, due to optical channels data-rates growing above re-configuration level (e.g. from 75Gbps to 100 Gbps), peaks appear in the energy consumption. The reason for that is the growth in the channel capacity when this moves at the next configuration level (e.g. from 25 to 50 Gbps, from 50 to 75 Gbps or from 75 to 100 Gbps) which requires a more complex modulation format. When using a higher modulation format, often more regenerators are needed and they are reserved, thus resulting in a peak of number of regenerators and also in a peak of consumed energy. Once the diurnal variation moves to a lower bit-rate in the channel capacity, the peak in power consumption disappears.

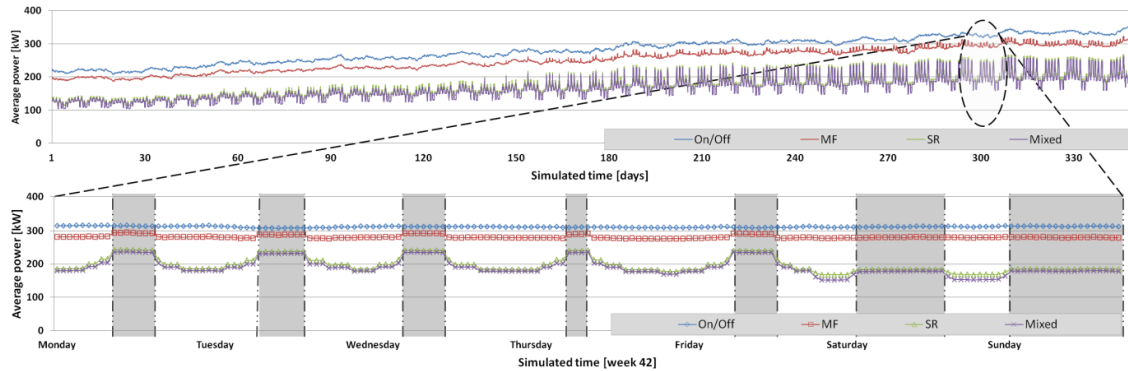


Fig. 3. Average power variation per year (top) and per week (bottom) for different power-adaptive network strategies in unprotected network.

In case of SR adaptation (green curve in Fig. 3) the average power consumption drops even more compared to MF adaptation and experiences a similar level of growth. Moreover, compared to the Baseline and MF adaptation cases, the energy consumption experiences a fluctuation which is very similar to the daily/weekly traffic fluctuations described in Fig. 1a, with diurnal variations and drastic traffic reduction for the weekend period. When the Mixed adaptation (MF and SR combined) is applied, the power consumption is even lower due to the increase of options provided by the two rate-adaptive strategies and the less consuming one is chosen.

Fig. 3 (bottom) shows a zoom over week 42 which gives a better detail on how the power consumption tracks the fluctuations of the optical channel capacity. Rate adaptive devices allow the reduction on power wastage due to traffic fluctuations, allowing the following power savings: 10,4% for MF scenario, 37% for SR scenario and 39,6% for Mixed case (shown in Fig. 6). Mixed case allows for highest savings at the expense of slightly increasing the complexity due to the need of performing an optimization algorithm to decide which adaptation (MF or SR) is optimum for a specific case.

Fig. 4 shows the relative difference between the average and peak traffic over diverse periods: daily, weekly and yearly. If power adaptation perfectly follows the traffic variations along the year, power savings could reach 56,8% for the studied traffic profile in case of unprotected networks. In case of protected networks, the dedicated protection connections should theoretically be available but ideally their associated power consumption can be 0. Thus, 100% savings could be achieved for the protection connections. The result is that in protected network scenario, the savings are an average between unprotected scenario and an ideal 100% energy savings scenario and thereby higher power savings are possible for protected network scenarios. Fig. 4 emphasizes also that 23,2% of the energy savings are given exclusively by the daily traffic variations while 12,5% of energy savings are assigned to the weekend traffic behavior. Moreover, 21,2% savings are given by the yearly growth.

B. Power savings in dynamic protected network

When deploying dedicated 1:1 protection spans in the network, a first change is given by the fact that the number of

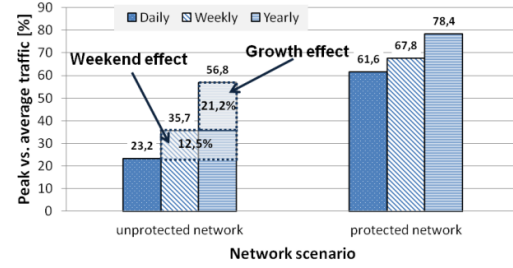


Fig. 4. The normalized difference of average and peak traffic.

set-up connections is doubled as indeed a connection will serve the working span and another one serves the protection span. In Fig. 5, the continuous growth of power consumption from Baseline scenario can be observed and a first important aspect is that the power value of the Baseline scenario is a more than 2 times higher compared to the one measured in Fig. 3 where no protection was deployed. This is explained by the fact that the protection spans are longer than the working ones (usually established on shortest path routes) and further regenerators are needed. Fig. 5 (bottom) shows a zoom over the week 42 and power variations following closely traffic variations in Fig. 1.

Fig. 6i shows the power consumption for the four adaptations and baseline scenario with emphasized values for idle and operational power. Idle state is present only in case of On/Off, MF and Mixed adaptations for protected network case where protection spans are deployed. The idle power has the same value for all three scenarios since protection span requirements are the same (cf. Section V). Moreover, the Baseline scenario and the SR scenario report a null idle power, because in both of these scenarios the protection spans are set-up with operational elements. Note that the power consumed by the idle devices accounts for 5% to 10% the total network power for On/Off scenario and Mixed scenario, respectively.

In Fig. 6i we also note that for the protected scenario the energy efficiency of SR and On/Off is inverted compared to the unprotected case. Indeed, for the unprotected case SR adaptation is less (51%) power greedy than On/Off scenario because active resources adjust their power to the actual carried

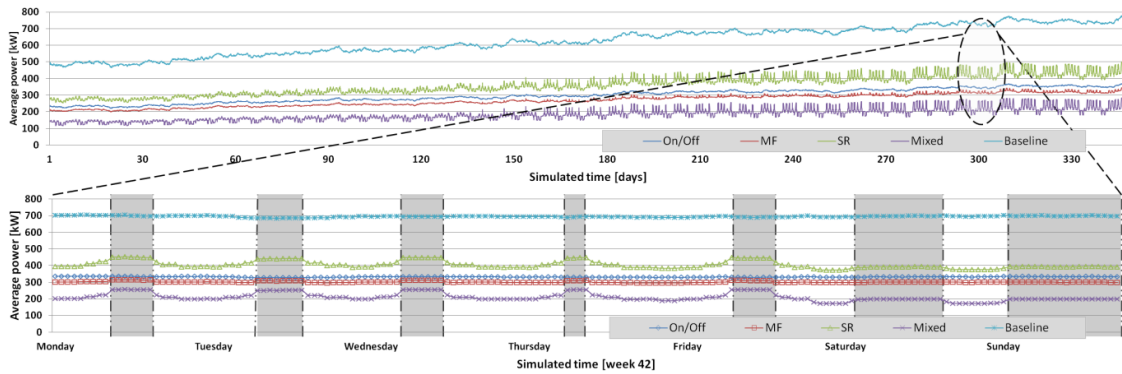


Fig. 5. Average power variation per year (top) and per week (bottom) for different power-adaptive network strategies in protected network.

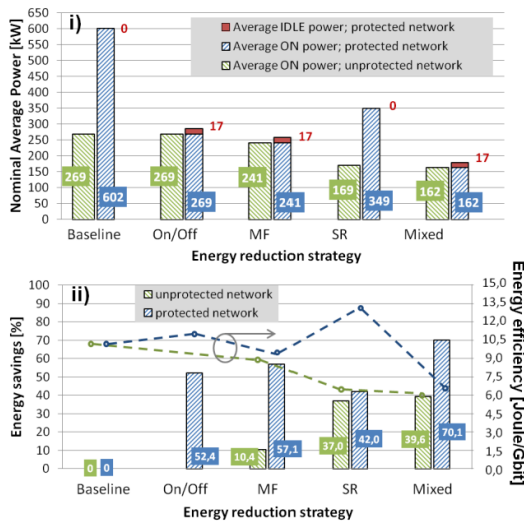


Fig. 6. Average operational and IDLE power consumption (i) and total energy savings and power efficiency (ii)

traffic; whereas for the protected case the power consumption for SR adaptation (349kW) is 22% higher than the On/Off adaptation one (286kW). This comes from the operational OE devices in the SR protected connections, which are configured at 25 Gbps (lowest power state of an SR adaptive device, i.e. 189W). Moreover, the On/Off scenario sets OE devices belonging to protection spans in idle state, having a consumption of only 18W (one tenth of the lowest SR power). For the protected case, also MF outperforms SR, conversely from the unprotected scenario. This is due to the capability of OE devices to be set in idle state. For the unprotected case, the Baseline and On/Off scenarios are identical and require the same average power. Fig. 6ii translates Fig. 6i results in terms of energy savings and power efficiency. We notice that higher savings are provided by the Mixed scenario, whatever the protection assumption. The energy efficiency degrades in protected scenarios because of the presence of idle spare resources. The power efficiency of the diverse strategies results: 8.9, 6.3 and 6 Joule/Gbit for MF, SR and Mixed respectively in unprotected scenario; while for the protected scenario is: 9.6, 12.9 and 6.6 respectively. The more efficient strategies integrate the capability of setting OE devices at idle state, thus making sleep-mode a necessary attribute for protected networks.

VII. CONCLUSIONS

Traffic experiences a continuous growth in optical networks. Protection mechanisms and over-provisioning require even more network capacity yielding to a huge number of deployed optoelectronic devices. The energy consumption of the network is proportional to the deployed number of devices and it is becoming more and more unsustainable. To control the whole network energy growth, a traffic-aware networking

approach is proposed and its implementation based on a GMPSL-based control plane is detailed. In this work we assess the overall energy of the network required by these strategies as a function of the observed traffic fluctuations; then we compare them for both protected and unprotected scenarios. We show that symbol-rate and modulation format adaptations provide different savings and power efficiency depending on network protection: the former is more efficient when only traffic fluctuations are considered, while the latter is more efficient when dedicated protection is accounted. Mixed adaptation (combining symbol-rate and modulation format) is the most efficient strategy, whatever the protection assumption is, providing 39.6% and 70% energy savings, respectively for the unprotected and protected cases.

ACKNOWLEDGMENT

The work in this paper was carried out with support from FP7 IDEALIST and Celtic Plus SASER projects and GreenTouch consortium.

REFERENCES

- [1] C. Lange, "Operator perspective on broadband network traffic evolution," in Proc. European Conference on Optical Communications, Amsterdam, Netherlands, Sep. 2012, paper Mo.2.D.1.
- [2] G. Maier et al., "Optical Network Survivability: Protection techniques in the WDM layer", Photonic Netw. Commun., vol. 4, no. 3-4, pp. 251-269, 2002.
- [3] A. Morea et al., "Traffic variation-aware networking for energy efficient optical communications", in Proc. Optical Network Design and Modeling, Brest, France, April 2013, pp. 29-34.
- [4] C. Lange et al., "Energy consumption of telecommunication networks," in Proc. European Conference on Optical Communications, Vienna, Austria, Sep. 2009, paper 5.5.3.
- [5] Y. Zhang et al., "Energy efficiency in telecom optical networks," Commun. Surveys Tuts., vol. 12, no. 4, pp. 441, 2010.
- [6] A. Morea et al., "Data rate adaptation for night-time energy savings in core networks," J. Lightw. Technol., vol. 31, no. 5, pp. 779-785, 2013.
- [7] R. Husermann et al., "Analysis of the energy efficiency in IP over WDM networks with load-adaptive operation", in Proc. ITG Conference on Photonic Networks, Leipzig, Germany, May 2011, paper 31.
- [8] O. Gerstel et al., "Elastic optical networking: a new dawn for the optical layer?," Commun. Mag., IEEE, vol. 50, no. 2, pp. S12-S20, Feb. 2012.
- [9] A. Morea et al., "Power management of optoelectronic interfaces for dynamic optical networks," in Proc. European Conference on Optical Communications, Geneva, Switzerland, Sep. 2011, paper We.8.K.3.
- [10] R. Casellas et al., "Design and experimental validation of a GMPLS/PCE control plane for elastic CO-OFDM optical networks," IEEE J. Sel. Areas Commun., vol. 31, no. 1, pp. 49-61, Jan. 2013.
- [11] A. Morea et al., "On the energy and cost trade-off of different energy-aware network design strategies," in Proc. Optical Fiber Communication Conference and Exposition, Anaheim, CA, Mar. 2013, paper OM3A.4.
- [12] J. Perello et al., "Power Consumption Reduction through Elastic Data Rate Adaptation in Survivable Multi-Layer Optical Networks", accepted for publication by Springer Photonic Network Communications Journal.
- [13] NORDUnet traffic with Customers - Average In traffic for Week 23 2014, <http://stats.nordu.net>.
- [14] AL. Berger et al., "RSVP Refresh Overhead Reduction Extensions", IETF RFC 2961, April 2001; www.rfc-editor.org/rfc/rfc2961.txt.
- [15] R. Husermann et al., "A set of typical transport network scenarios for network modelling," in ITG-Conference Photonic Networks, Leipzig, Germany, May 2004, pp. 65-71.

E. Power efficient service differentiation based on traffic-aware survivable elastic optical networks

Power Efficient Service Differentiation Based on Traffic-Aware Survivable Elastic Optical Networks

Ioan Turus, Anna Manolova
Fagertun and Lars Dittmann
Technical University of Denmark
DK-2800, Lyngby, Denmark
iotu@fotonik.dtu.dk

Annalisa Morea
and Dominique Verchere
Optical Networks Department
Bell Labs Centre de Villars
Nozay, France

Josva Kleist
NORDUnet A/S
DK-2700, Kastrup, Denmark

Abstract— This study assesses the feasible energy savings when defining different service classes based on protection schemes in core optical networks. We propose a dedicated energy saving strategy for each of the service classes in order to minimize the overall power consumption of the network. Four Classes of Service are considered: platinum, gold, silver and best effort. Platinum connections benefit from a 1+1 protection scheme, gold connections and silver connections are assigned to a 1:1 protection with the difference that in case of gold connections the same pair of transponders is shared by the working and protection sections. Best-effort connections do not have any associated protection. Two scenarios are implemented and compared. The first, the baseline approach, does not take into account any traffic-aware strategies while the second one, the proposed approach, includes energy reduction strategies taking into account the sleep-mode capability of the opto-electronic devices as well as the elastic data-rate adaptation based on symbol-rate and modulation-format reconfigurations. The results show that in the baseline approach the power consumption is strongly dependent on the ratio between the different service classes while for the proposed approach the difference in power consumption is almost negligible. Moreover, in case of the proposed approach, silver service class can benefit for superior quality of service compared to the gold service class, due to the grooming mechanism.

Keywords—energy; priority; elastic; services; protection.

I. INTRODUCTION

Today, the core optical networks run by telecom operators experience various challenges due to the continuously expansion of the network coverage as well as due to the continuously increase of the transported traffic estimated to be about 30%-60% per year [1]. To guarantee a good operation of the network, it is important that every connection within a core optical network is

guaranteed by a certain level of protection and restoration is available accordingly [2], whatever the failure (physical and logical) affecting the network.

Considering the continuous traffic growth as shown in Fig. 1 and the static deployment of the opto-electronic (OE) devices today, resource overprovisioning has to be applied in order to cope with the forecasted traffic growth. Moreover, the traffic experiences predictable variations such as diurnal and weekly [3] (depicted in Fig. 1) and the network resources are not able to adapt to such variations and they are deployed to the peak traffic, resulting in further resource overprovisioning. This results in a very inefficient usage of the deployed network resources.

A consequence of such inefficient usage of resources translates into inefficient energy consumption. It is estimated that a 1200% increase of the traffic will determine an increase of 150% of the energy in the overall network, according to the forecasts in [4] and [5]. To improve the energy efficiency of the networks, two methods are investigated: the introduction of the sleep-mode state in OE devices and elastic network devices. Thanks to the introduction of elastic OE devices [6], the core optical network has the possibility to reconfigure its resources according to the traffic demand. When sleep-mode capability of the OE devices is taken into account together with the elastic data-rate adaptation, significant energy savings can be accounted as described in [7].

The remainder of this paper is organized as follows: Section II details the traffic-aware networking approach. In Section III, the four different Classes of Services (CoSs) are detailed for both the baseline and the proposed approaches. Section IV presents the implemented control functions as part of the GMPLS control plane. In Section V the simulation setup is presented. Sections VI and VII provide the results and conclude the paper, respectively.

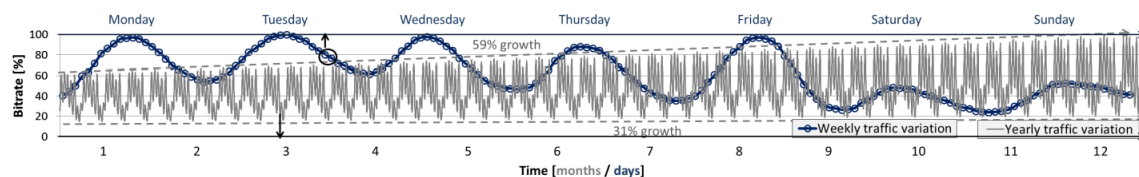


Fig. 1. Traffic variation of an optical channel in one week and one year variation period.

TABLE I. TRANSPONDERS POWER AS A FUNCTION OF SYMBOL-RATE (SR) AND MODULATION FORMAT (MF).

Payload (Gbps)	SR (GBd)	MF	Reach (km)	Power (W)
100	28	PDM-QPSK	600	350
	75	28 PS-QPSK	900	350
50	21	PDM-QPSK	600	255
	28	PDM-BPSK	1250	350
25	14	PDM-QPSK	600	206
	28	SP-BPSK	1500	350
	14	PDM-BPSK	1250	206
	7	PDM-QPSK	600	189

II. TRAFFIC-AWARE NETWORKING

Considering the daily and weekly traffic fluctuations as well as yearly traffic growth, the network has to be able to adapt to the variations of the traffic demand [8]. Thereby, a traffic-aware networking concept will take into account the elastic capabilities of the OE devices, the sleep-mode operations as well as grooming approaches and they will enable network reconfiguration according to the traffic demand characteristics.

The data-rate adaptation capability relies on the possibility of adapting the modulation format (MF) and/or the symbol-rate (SR) of an OE device. When only MF is changed, power reduction when passing from a more complex modulation format to a simpler one is possible only if there is a bypass of regenerators due to increased optical reach associated to the decrease of the MF complexity. Moreover, energy savings require the sleep-mode capabilities in order to allow the turn off of intermediary regenerators. When only SR is changed, power reduction is allowed since the power of an OE device scales down linearly with the reduction of its symbol-rate, as demonstrated in [9]. When SR adaptation is used, sleep-mode capability is not required since no regenerator is skipped because the reach is SR independent. When both MF and SR can be changed in a reconfiguration, the adaptation is called Mixed and it relies on the optimum choice in terms of power consumption between MF and SR adaptation.

The sleep-mode capability is based on the possibility of changing the power state of the OE device. This results into a totally or partially powered device (*on* and *idle* states, respectively) or a switched off device (*down* state). When the device is in *on* state it runs with its all specifications enabled.

When the OE device is in *idle* state, it consumes lower power compared to *on* state and it is able to switch fast to *on* state in order to improve network QoS (bandwidth, latency, availability etc.) for the new traffic demands, as shown in [7].

Grooming capability is applied whenever routing a new demand. A policy controller checks for every new connection set-up if there is an existing optical channel which has the same source and destination pair. If at least one such optical channel is available and the sum of the optical capacity of the two channels does not exceed 100 Gbps (OE device maximum capacity, shown in Table I) during the foreseen common lifetime of the two connections, then grooming is considered feasible. Thus, the incoming connection is not established over a new path and new set of OE devices but it is groomed into the existing connection.

If MF and/or SR adaptation is performed, the channel data-rate is re-configured and the connection capacity changes. In this study, the considered rate-adaptive OE devices can handle 25, 50, 75 and 100 Gbps, like in [9] and only mixed adaptation is taken into account. Table I provides the power consumption values of the transponders working at a given rate and modulation format. The power consumption of a regenerator is twice the transponder's one as they are realized by two transponders back-to-back. When OE devices are idle their consumption is 18W for a transponder and 36W for a regenerator [7]. As in this study we also want to emphasize the impact of regenerators in the network power consumption, reach values are reported in Table I, but they are halved compared to values reported in [7] to emphasize the reduction of regenerators in the considered network topology.

III. CLASSES OF SERVICES

In order to provide different levels of protection, four Classes of Services (CoS) are defined: Platinum, Gold, Silver and Best Effort. The four CoS are defined for both baseline case (where no traffic-aware networking is present) and for the proposed case where different capabilities of traffic-aware networking approach are included. The service classes are defined as follows (Fig. 2):

Baseline approach:

- **Platinum CoS demand** (Fig.2 a): working section runs statically (no adaptations and no sleep-mode is present) at 100 Gbps and includes grooming where possible; 1+1 protection route is set-up statically;

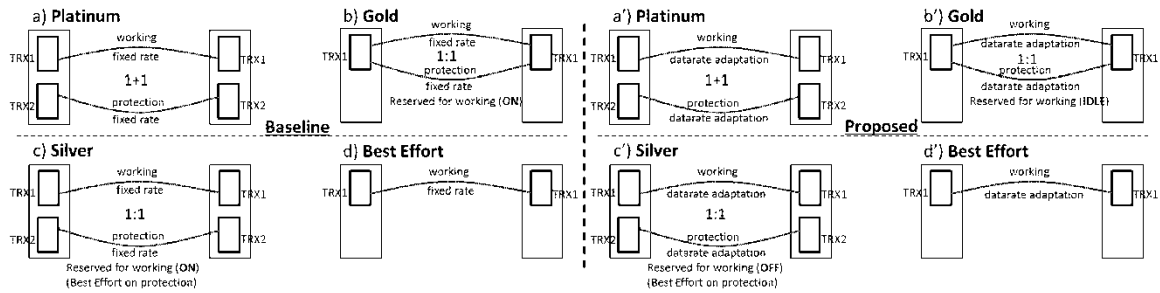


Fig. 2. Service Class (CoS) definition for baseline and proposed approaches.

- **Gold CoS demand** (Fig.2 b): working section runs statically at 100 Gbps and includes grooming where possible; 1:1 protection is deployed with shared transponders and protection sections are set into mode *on*;
- **Silver CoS demand** (Fig.2 c): working section runs statically at 100 Gbps and includes grooming where possible; 1:1 protection is deployed and protection sections are set-up for working sections; where possible, best effort traffic passes on the protection sections, otherwise resources are *on* and unused;
- **Best Effort CoS demand** (Fig.2 d): is configured statically at 100 Gbps and does not include any protection.

Proposed approach:

- **Platinum CoS demand** (Fig.2 a'): working section runs with data-rate adaptation enabled (mixed adaptation); 1+1 protection is deployed with protection section configured with data-rate adaptation as well;
- **Gold CoS demand** (Fig.2 b'): working section runs with data-rate adaptation enabled (mixed adaptation); 1:1 protection is deployed with shared transponders and protection sections have the regenerators reserved in *idle* mode;
- **Silver CoS demand** (Fig.2 c'): working section runs with data-rate adaptation enabled (mixed adaptation); 1:1 protection is deployed with protection section having the regenerators reserved in mode *off*; when possible, best effort traffic is groomed on protection sections that are activated;
- **Best Effort CoS demand** (Fig.2 d'): working sections run with data-rate adaptation enabled and no protection is considered.

The grooming mechanism which is responsible to map best effort connections into the protection sections of the Silver connections performs specific operations in the baseline and proposed approaches. Considering the fact that the traffic is dynamic and demands have a time-delimited duration, the grooming operation between two connections is justified for the time they overlap in time. In case of the baseline approach, when the grooming conditions are met, the Best Effort connection is directly established over the powered (mode *on*) OE devices of the Silver connection protection section. If the Silver connection expires, the protection section and associated connection are not torn down until the best effort connection finishes its duration. In case of the proposed approach, when the grooming conditions are met, a signaling procedure sets up the protection section of the Silver connection from mode *off* to *on* and afterwards the Best Effort connection is groomed. When the Best Effort connection expires, the OE devices of the protection section are released to mode *off* but they are left reserved for the Silver working section until the end of life of the Silver connection.

IV. CONTROL FUNCTIONS

GMPLS control plane is used for controlling and configuring the analyzed network. RSVP-TE is used to set-up and tear-down connections and to reconfigure the power state (sleep-mode, SR and MF configuration) of an optical channel. Protocol extensions are used to encapsulate the required elastic

parameters and Trigger messages [10] were extended for performing the required re-configurations [9].

Similarly to the implementation we proposed in [11], the GMPLS control plane follows the computations performed in a policy controller which decides when adaptation and/or recovery are required. Re-configuration of the existing optical channels is performed in the proposed approach which includes data-rate adaptation. When an MF adaptation is performed, the controller in the source nodes computes another set of regenerator placement along the path, according to the reach of the chosen modulation format. Afterwards, sleep-mode strategy is applied for the required regenerators and no changes on add/drop transponders are operated. When sleep-mode strategy is applied, an OE device can be either in operational state (powered *on*) or be set to *idle* or *off* state. When an SR adaptation is performed, a new symbol-rate value has to be advertised starting from the source node to all active OE devices associated to this channel. In this study, the adaptation taken into account is a mixed adaptation, thus, SR and MF adaptations are taken into account at the same time. A Trigger PATH message transports the new MF and/or SR information from source to destination into dedicated sub-objects while a Trigger Resv message confirms the reservation and/or the new configuration of the OE devices.

V. SIMULATION IMPLEMENTATION

A German-17 node network, depicted in Fig. 3, is used as reference topology for studying the proposed scenarios. A dynamic traffic is deployed in the network. Demands are generated in all nodes and connections are uniformly distributed between source and destination pairs. Each connection has a peak capacity assigned with equal probability between 50, 75 or 100 Gbps. Demands are requested with an exponentially distributed mean inter-arrival time of 4 hours and exponentially distributed holding time with a mean of 80 hours resulting 20 Erlangs load per node. Every link carries up to 80 wavelengths and the total input traffic in the year does not experience blocking due to lambda congestion.

The four different CoS are distributed with a pre-defined ratio to the connection requests. For evaluating the power consumption associated to CoS, the implemented distributions are as follows:



Fig. 3. German 17 nodes network [12].

- Only (100%) Platinum, Gold, Silver or Best Effort traffic;
- Only Silver and Best Effort traffic (with a percentage of 10, 20, 30, 40 and 50% of Silver traffic);

For the CoS distribution assessment, the implemented distributions take into account the total share of Gold and Platinum traffic together which represents 0, 10, 20, 30, 40 and 50% of the total traffic while from the remaining traffic the Best Effort is distributed with a percentage of 25, 50 and 75%. Moreover, the distributions are as follows according to the ratio between Gold and Platinum traffic within their common share:

- Gold traffic 50% and Platinum traffic 50%;
- Gold traffic 25% and Platinum traffic 75%;
- Gold traffic 75% and Platinum traffic 25%;

When a connection request arrives at a source node, it is automatically marked with a CoS and served accordingly. In the baseline scenario no data-rate adaptation and no sleep-mode capability are enabled while they are only enabled in the proposed approach scenario. A policy controller is distributed to every node and it enforces the configured grooming and adaptation mechanisms.

VI. RESULTS

A. Power consumption associated to CoS

The four CoS have been defined and implemented in both baseline and proposed approaches. Fig. 4a) shows the average power consumption associated to scenarios where all demands have the same CoS. It can be seen that in the baseline approach the power consumption is always higher compared to the proposed approach and this is because the network configuration does not adapt to the traffic fluctuations nor to the traffic growth.

In case of the baseline approach, it can be seen in Fig. 4a) that both scenarios where Silver and Platinum connections are distributed 100%, the power consumption is the same. This is explained by the fact that, as depicted in Fig. 2, both CoS use the same number of transponders and the same type of protection path. These two scenarios experience also the maximum consumed power from all analyzed scenarios. The scenario where Best Effort connections are present 100% is the one consuming the lowest amount of power and that is because of no

protection paths provided and no protection overprovisioning is done. This power value is the target of the best power efficient protection method. When we consider the scenario associated only to Gold connections, we observe a power consumption that is the average of the power associated to BE (Best Effort) and Platinum scenarios, as transponders are shared between working and protection sections.

When the proposed approach is taken into account, the power consumption is lowered and the highest power consumption is obtained for Platinum CoS scenario only. As a difference from the baseline approach, in the proposed approach the Silver CoS scenario now consumes the lowest amount of power, together with the Best Effort only scenario. This is given by the fact that for Silver connections the OE devices on the protection sections are reserved and configured in *off* mode so no extra power consumption is experienced. The Gold scenario in the proposed approach obtains slightly higher power consumption: the little difference being provided by the regenerators on the protection sections which are reserved on *idle* mode. It is important to note that the power consumption associated to the Platinum scenario in the proposed approach is more than twice the power associated to Best Effort or Silver scenarios. The reason for this is that the protection sections are usually longer, in terms of number of hops, than the working sections and this determines a higher number of regenerators as well as higher power consumption associated to a protection section compared to a working section.

Fig. 4b) presents five scenarios where only Silver and Best Effort connections are deployed in the network. The goal of this choice is to show the effect of grooming Best Effort connections into protection sections associated to Silver connections. For the baseline approach, the two lines associated to the right axis describe the increase in power consumption (dashed line) and the increase in number of channels (dotted line) relative to the case where only Best-Effort traffic is present in the network. Note that when Silver connections are introduced into the network, the total number of channels becomes higher because Silver connections create also protection sections/channels. Thus, Fig. 4b) emphasizes that the relative increase of the power consumption, when Silver connections are introduced in the network, is lower compared to the increase of total number of

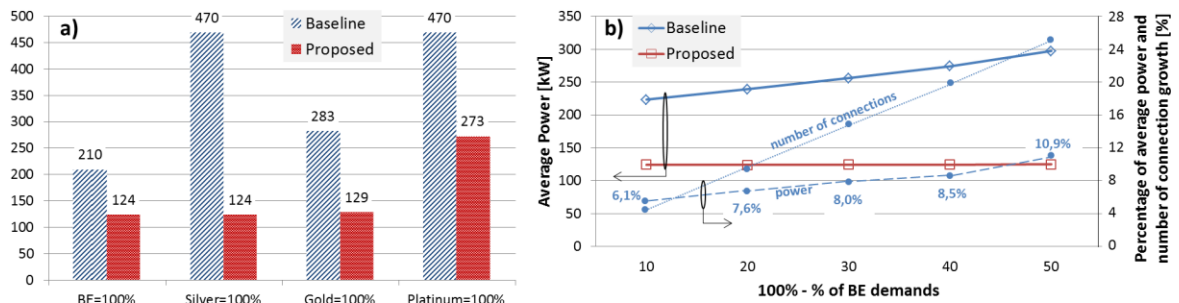


Fig. 4. Average power consumption for different scenarios where all demands have the same Service Class in Baseline and Proposed approaches (a) and Average power and growth of the average power and number of channels for different shares of Silver and Best Effort traffic (b)

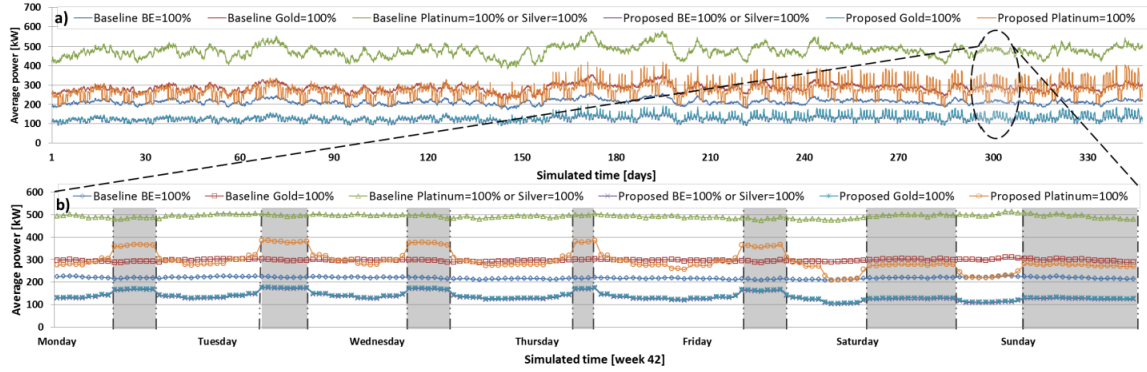


Fig. 5. Average power variation per year (top) and per week (bottom) for different Service Classes deployments.

channels. As an example, when 50% of the connections in the network are classified as Silver, the average power consumption grows with 10.9% while the total number of channels in the network grows with 25%. This is explained by the fact that a significant number of Best Effort connections are groomed into the protected sections associated to Silver connections. Moreover, particularly for the case where 10% of the connections are Silver (or generally, when there are very few Silver connections in the network) the growth in the power consumption is higher than the increase in number of connections because very few or no grooming operations can be performed (due to low probability of a Best Effort connection to find an available Silver connection protection section).

Fig. 4b) also shows that in case of the baseline approach, the average power consumption is growing with the increasing share of Silver connections (blue line) while in case of the proposed approach, the average power consumption is almost independent of the share of Silver connections (red line). This is explained by the fact that in the proposed approach not only data-rate adaptation is possible and the network can follow the traffic fluctuations but also the protection sections of the Silver connections are only reserved and maintained in mode *off*. Moreover in this case, when grooming is possible, the protection section is reconfigured from mode *off* to *on* during the lifetime of the groomed Best Effort connection. This determines however an important effect: when the protection section of a Silver connection holds Best Effort traffic, the resulting Quality of Service provided by this connection is higher than the one

provided by the Gold connections. The reason is that the protection section has OE devices already *on*, while Gold connections have the OE devices in the protection section always configured in *idle* mode. Thus, a restoration for Silver connections is faster than the one for Gold connections. The drawback however, which determines Silver connections to be classified lower compared to the Gold ones, is that Silver connections cannot guarantee that Best Effort traffic is always available to be groomed on the Silver protection sections and it is less likely that the Best Effort connection duration is going to overlap for the whole duration of the Silver connection.

Fig. 5a) confirms the results in Fig. 4 by showing the average power variation during the one year simulated time. It can be observed that the highest power levels are obtained for the baseline one-service scenarios containing only Platinum and Silver connections and that in all baseline scenarios the power has a random variation – given by the random arrival of the connection demands. In case of the proposed approach scenarios, for all the four cases it can be easily seen (a zoom to week 42 is provided in Fig. 5b) that they follow both the diurnal and the weekly traffic variations because of the opportunity of adapting power adaptation (sleep-mode and symbol/modulation rate adaptation).

B. CoS distribution assessment

An interesting aspect within service class differentiation is to assess the power consumption when the four CoS are combined in the same network scenario. Fig. 6 shows three different cases

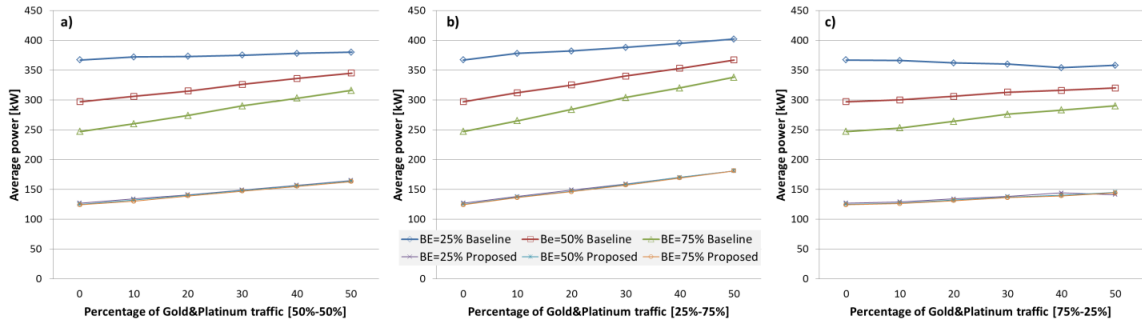


Fig. 6. Average power consumption for different Service Classes distributions in a combined scenario.

where the share of Gold and Platinum traffic taken together is fixed and represents 0, 10, 20, 30, 40 or 50% of the total connection demands in the network while the percentage of Best Effort and Silver traffic varies. In Fig. 6a) one notices that in all cases the Gold and Platinum CoS share equally their part of connection demands (50%-50%). Thus, for the baseline scenario it can be observed that for all three distributions of Best Effort traffic (25, 50 and 75%) the power consumption grows with the increase of the Gold and Platinum traffic share. Moreover, the maximum power consumption is obtained when the number of Best Effort demands is minimum - which is equivalent to maximum number of Silver demands.

When analyzing the proposed approach in Fig. 6a) it can be noticed that the differences between the three distributions of Best Effort traffic are negligible in terms of power consumption. This is explained by the fact that Silver connections always set their protection sections with OE devices in mode *off* and do not provide extra power consumption. However, when Best Effort connections are groomed into the protection sections of the Silver connections, it can lead to slightly higher power consumption of the groomed Best Effort connection compared to the Best Effort only case. The reason for this is that the protection section of the Silver connection runs usually on a longer path compared to the working section.

In Fig. 6b) and 6c) the scenarios are different in terms of the ratio between Gold and Platinum demands within their assigned share of connections. In Fig. 6b) Gold connections are 25% and Platinum connections are 75% while the opposite ratio is given in Fig. 6c). When comparing the two figures and referring them to Fig. 6a) it is observed that when the number of Platinum connections is higher, the average power consumption experiences a steeper increase (see Fig. 6b) for the baseline scenario. The opposite case is when we decrease the share of Platinum connections. This is explained by the fact that Platinum connections do not allow grooming of Best Effort connections into their protection sections and thus no energy reductions can be done. When comparing the same figures for the proposed approach, similar conclusion is obtained indicating that negligible differences in power consumption are achieved for the different distributions of Best Effort and Silver traffic. Moreover, when the ratio of Platinum connections is higher (see Fig. 6b), the growth of power consumption is steeper when increasing the share of Gold and Platinum connections together.

VII. CONCLUSIONS

Traffic experiences nowadays a continuous growth as well as specific fluctuation patterns in core optical networks. Moreover, protection mechanisms add an even higher demand for capacity and consequently determine higher power consumption.

A power efficient service differentiation is proposed and it takes into account different protection implementations as well as traffic-aware energy reduction approaches. Four classes of services are defined: Platinum, Gold, Silver and Best Effort based on different 1-1 and 1:1 dedicated protection schemes. In the

baseline approach, the traffic growth and traffic fluctuations are not taken into account and the influence of the different distributions of service classes is assessed. In the proposed approach, traffic-aware strategies such as data-rate adaptation (i.e. modulation format and/or symbol rate adaptation) and sleep-mode capabilities are implemented as well. Results show that in the baseline approach, Platinum and Silver demands consume a similar amount of power and account for the most of the power consumed in the network. Moreover, in the baseline approach the ratio between the different service classes distribution highly influences the power consumption.

In the proposed approach, thanks to the traffic-aware strategies, the dependence of the power consumption on the service class distribution becomes negligible. Moreover, when grooming mechanism is applied and a Best-Effort connection is transported over the protection section of a Silver connection, a higher quality of service is enabled from the protection point of view to the Silver connection; which can be considered superior to the Gold connection class.

ACKNOWLEDGMENT

The work in this paper was supported by FP7 IDEALIST, Celtic Plus SASER projects and GreenTouch consortium.

REFERENCES

- [1] C. Lange, "Operator perspective on broadband network traffic evolution," in Proc. European Conference on Optical Communications, Amsterdam, Netherlands, Sep. 2012, paper Mo.2.D.1.
- [2] G. Maier et al., "Optical Network Survivability: Protection techniques in the WDM layer", *Photonic Netw. Commun.*, vol. 4, no. 3-4, pp. 251-269, 2002.
- [3] NORDUnet traffic with Customers – Average In traffic for Week 23 2014, <http://stats.nordunet.net>.
- [4] C. Lange et al., "Energy consumption of telecommunication networks," in Proc. European Conference on Optical Communications, Vienna, Austria, Sep. 2009, paper 5.5.3.
- [5] Y. Zhang et al., "Energy efficiency in telecom optical networks," *Commun. Surveys Tuts.*, vol. 12, no. 4, pp. 441, 2010.
- [6] O. Gerstel et al., "Elastic optical networking: a new dawn for the optical layer?," *Commun. Mag., IEEE*, vol. 50, no. 2, pp. S12-S20, Feb. 2012.
- [7] A. Morea et al., "Power management of optoelectronic interfaces for dynamic optical networks," in Proc. European Conference on Optical Communications, Geneva, Switzerland, Sep. 2011, paper We.8.K.3.
- [8] A. Morea et al., "Traffic variation-aware networking for energy efficient optical communications", in Proc. Optical Network Design and Modeling, Brest, France, April 2013, pp. 29-34.
- [9] A. Morea et al., "Data rate adaptation for night-time energy savings in core networks," *J. Lightw. Technol.*, vol. 31, no. 5, pp. 779-785, 2013.
- [10] AL. Berger et al., "RSVP Refresh Overhead Reduction Extensions", IETF RFC 2961, April 2001: www.rfc-editor.org/rfc/rfc2961.txt.
- [11] I. Turus et al., "Energy savings in dynamic and resilient optical networks based on traffic-aware strategies", in Proc. 16th International Telecommunications Network Strategy and Planning Symposium, Funchal, Madeira Island, Portugal, Sept. 2014.
- [12] R. Husemann et al., "A set of typical transport network scenarios for network modelling," in ITG-Conference Photonic Networks, Leipzig, Germany, May 2004, pp. 65-71.

F. OPEX savings based on energy efficient strategies in NREN Core Optical Networks

OPEX Savings Based on Energy Efficient Strategies in NREN Core Optical Networks

Ioan Turus¹, Anna Manolova Fagertun², Josva Kleist¹

NORDUnet A/S, Kastruplundgade 22, DK-2770 Kastrup, Denmark, iotu@nordu.net Phone: +45 31 62 78 17

Technical University of Denmark, Copenhagen, Denmark, anva@fotonik.dtu.dk

Abstract

The common practice for optical network operators today is to deploy optical resources based on over-provisioning towards the maximum expected amount of traffic in the network. This is a safe strategy and it takes into account the currently static nature of the optical network design, where new wavelengths and new circuits are established based on a pre-defined dimensioning plan. However, because of the continuous increase in the overall traffic demand (estimated to be between 30% and 60% per year [1]) as well as due to the more and more heterogeneous behavior of the incoming requests – the over-provisioning deployment strategy becomes less and less efficient. This is a challenging aspect especially in NREN environments where new and state of the art services are being proposed or requested (e.g. Photonic Services) and their requirements are often hard to be predicted. Moreover, in terms of energy consumption, significant savings can be obtained and accounted into OPEX (Operational Expenditure) by taking into account a more efficient usage of the opto-electronic resources (such as transponders or regenerators). There are more strategies proposed in the literature to enhance the energy consumption in core optical networks. One proposal is to define different operational states for the opto-electronic components – OFF, IDLE and ON – which correspond to different levels of energy consumption. Another solution is to use advanced transponder architectures (i.e. elastic or flexible transponders, introduced in [2]) which are able to tune the symbol-rate of an optical circuit and thus determine a variable consumption for the transponder. Simulations show that when deploying the proposed energy reduction strategies and while taking into account weekly fluctuations and traffic growth, the overall energy consumption can be reduced with 48% for NORDUnet network scenario and with 50% for a GEANT network scenario.

Keywords

Energy; efficiency; elasticity; transponder; GMPLS;

1. Introduction

One main challenges experienced today by National Research and Educational Networks (NRENs) is related to the increasing operational expenditure (OPEX) for running the core optical networks. Within the complex composition of the OPEX, one important part is related to the energy consumption required to run the network. A challenge today is that considering an overall traffic growth of 60%, as shown in Fig. 1(left), strong overprovisioning has to be applied and network is run at a configuration planned to cope with traffic increase in 2-3 years from now – despite the fact that currently the network is over-dimensioned. Moreover, the traffic in aggregated core links experienced very predictable fluctuations such as day/night fluctuations and overall traffic drops during the weekend – as shown in Fig. 1(right).

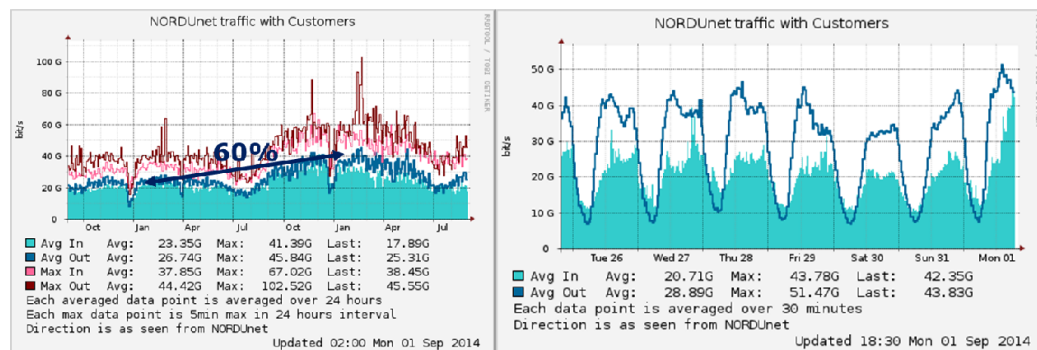


Figure 1. NORDUnet traffic with Customers during 2 years (left) and during one week (right) [3].

The predictable traffic fluctuations and traffic growth can be used as an opportunity to adapt the data-rate and the overall power consumption of the network. Thus, specific energy reduction strategies have to be considered and linked to the traffic variations.

2. Traffic-aware energy savings strategies

The proposed energy savings strategies take into account two approaches: the sleep-mode and data-rate adaptation capability of the OE devices (i.e. transponders and regenerators).

2.1 Sleep-mode

Sleep-mode refers to the capability of the OE devices to switch between three available power states: ON, IDLE and OFF, as proposed in [4]. When an OE device is in IDLE state, it only consumed a negligible amount of power compared to ON state (as seen in Table I) and at the same time it is able to switch very fast to state ON. Despite the fact that state OFF does not consume any power, it is relatively slow process to switch from state OFF to state ON due to the time required to power and stabilize the lasers [4]. Moreover, as shown in Table I, note that the considered regenerators have a two back-to-back transponders configuration and thus they consume the double amount of power for the same state compared to a transponder.

	ON	IDLE	OFF
Power (TRX)	350W	16W	0W
Power (REG)	700W	32W	0W

Table I. Power consumption of 100G PDM-QPSK OE devices in ON, IDLE and OFF modes [4].

2.2 Data-rate adaptation:

Data-rate adaptation refers to the capability of the elastic opto-electronic devices to tune their symbol-rate or modulation format configuration. Thereby, the modulation format (MF) adaptation is realized by changing the configured modulation format for all opto-electronic devices along the path and thus varying the configured data-rate. The result of this operation is that by changing the modulation format, also the transparent reach is changed for that connection and if this is used together with sleep-mode capability, certain regenerators can be turned to mode OFF or IDLE when the reach increases. The symbol-rate (SR) adaptation is realized by changing the configured symbol-rate format for all opto-electronic devices along the path. This procedure does not require any sleep-mode capabilities and it has been demonstrated in [5] that the power consumption of an elastic transponder is proportional to the configured symbol-rate. Thus when the data-rate decreases, the symbol-rate of the opto-electronic devices along the path can be decreased and thus the overall power associated to that connection is decreased. Table II shows a detailed configuration of the elastic transponder for the four possible configurations: 25, 50, 75 and 100 Gbps and their assigned power consumption and transparent reach. A mixed adaptation is considered to be the optimum choice between MF and SR adaptations in terms of resulted power consumption.

Payload (Gbps)	SR (GBd)	MF	Reach (km)	Power (W)
100	28	PDM-QPSK	1200	350
75	28	PS-QPSK	1800	350
	21	PDM-QPSK	1200	255
50	28	PDM-BPSK	2500	350
	14	PDM-QPSK	1200	206
25	28	SP-BPSK	3000	350
	14	PDM-BPSK	2500	206
	7	PDM-QPSK	1200	189

Table II. Power consumption of transponders at different elastic data-rate configurations [5].

3. Implementation

In order to evaluate the energy savings provided when traffic-overprovisioning is considered, two different network topologies are used: a GEANT pan-European network and a NORDUnet regional network, as depicted in Fig. 2. Traffic demands are generated in every node and they are uniformly distributed with maximum peak capacities of 50, 75 and 100 Gbps. In terms of dynamicity, the demands are described by an exponentially distributed mean inter-arrival time of 1.6 hours and duration of mean value of 38 hours which determines a load per node of 24 Erlangs. Every link in the network was configured with 80 lambdas and no blocking was experienced due to lambda availability.

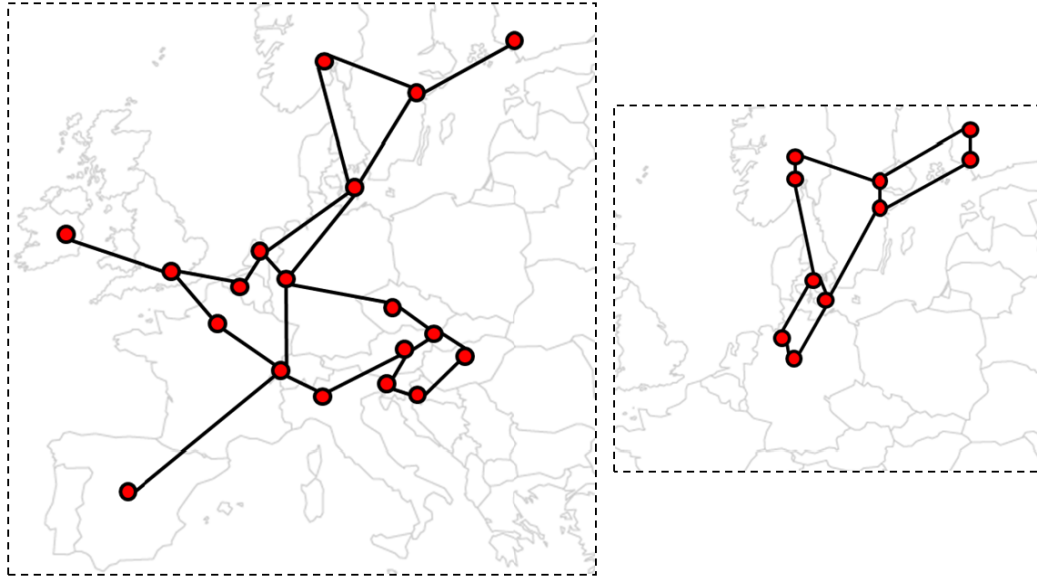


Figure 2. GEANT (left) and NORDUnet (right) core optical topologies.

The implementation considers for every demand a traffic pattern which is derived from observations on NORDUnet traffic with customers [3]. The pattern considers both daily traffic fluctuations and the weekend drops and the observations are averaged and sampled with 1h sampling period from data given in [3] as it can be seen in Fig. 3(top). Moreover, a 60% average traffic increase is considered during one year simulated period, as depicted in Fig. 3(bottom).

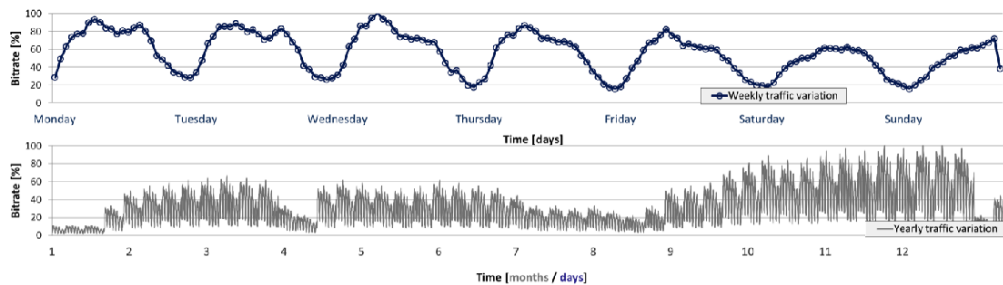


Figure 3. Average traffic variation per week (top) and per year (bottom).

Four energy savings strategies are implemented and applied on the two reference networks and over the proposed traffic model as follows:

- **Fixed:** all demands are configured with connections of 100 Gbps (PDM-QPSK and 28 Gbd) independent on the incoming traffic demand variation;
- **MF:** a policy controller verifies the variation of the data-rate within every connection and performs a reconfiguration of the MF when the data-rate varies between 25, 50, 75 and 100 Gbps;
- **SR:** a policy controller verifies the variation of the data-rate within every connection and performs a reconfiguration of the SR when the data-rate varies between 25, 50, 75 and 100 Gbps;
- **Mixed:** a policy controller verifies the variation of the data-rate within every connection and performs a reconfiguration of both SR and MF by choosing the optimum choice to minimize the overall energy associated to current connection;

4. Results

The average power consumption during 1 year simulated time is depicted in Fig. 4 a) and c) for NORDUnet and GEANT network scenarios respectively. It can be observed in Fig. 4 a) for NORDUnet scenario that the power consumption in the Fixed scenario is relatively constant and the small fluctuations are given by the random

arrival or the incoming demands. However, the variation associated to the Fixed scenario does not follow any diurnal or weekly traffic fluctuations as shown in Fig. 3. Moreover, it can be observed in Fig. 4 b) that for both MF, SR and Mixed scenarios the power adapts to the traffic fluctuations. As a general trend, SR adaptation allows a lower power consumption while the Mixed adaptation decreases even more the overall power consumption.

In Fig. 4 c) it can be seen that for GEANT network the power consumption for the Fixed scenario is relatively constant and more than double compared to the one associated to NORDUnet network (800 kW vs. 250 kW) and this is explained by two factors: the longer links which demand more regenerators in GEANT network and the higher number of nodes which all generate 20 Erlang demands for GEANT network. Moreover, comparing Fig. 4 b) and Fig 4 d) it can be observed that for GEANT scenario the power associated to MF adaptation is lower than the one associated to SR adaptation (however, it is higher than in Mixed scenario) and this is explained by the fact that in average more regenerators are deployed for connections in GEANT network and that allows a more efficient MF adaptation.

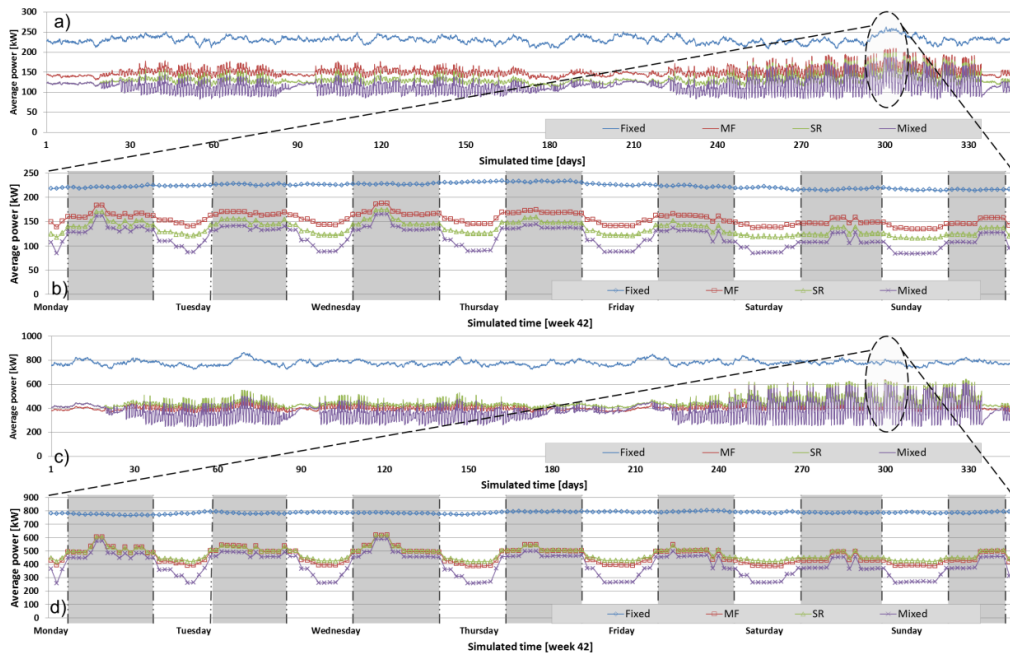


Figure 4. Average power variation per year for NORDUnet (a) and GEANT (c) and average power per week for NORDUnet (b) and GEANT (d) network scenarios.

In order to have a reference of possible savings to be achieved for the analyzed traffic pattern, the peak to average traffic was computed and depicted in Fig 5. (left) for the different types of fluctuations and traffic growth. Thus, it can be seen that if the power can likely adapt to the daily fluctuations only, a possible 32% power reductions could be achieved. Moreover, if the weekend drops are taken into consideration, an extra 11% power savings can be accounted and an extra 26% would be possible when considering the overall yearly growth.

Results in Fig. 5 (right) show the average power savings achieved during one year for the two considered network scenarios when applying the three proposed energy reduction strategies. It can be noted that MF adaptation enables significantly higher savings in GEANT compared to NORDUnet network scenarios (45 vs 34%). This is explained by the fact that GEANT network has a higher foot-print and thus connections requested in GEANT network are longer and require more regenerators. Thus, when a path is long enough and has a significant number of regenerators – the MF adaptation can play an important role in releasing a number of these regenerators when the data-rate decreases. This is not the case in relatively small network footprints, like

NORDUnet, where path are shorter and usually demand fewer regenerators making it less likely to bypass many regenerators with MF adaptation when data-rate decreases.

Moreover, Fig. 5 (right) shows that SR adaptation has similar performance in the two network scenarios, thus enabling energy savings of around 42%. The most efficient approach – the Mixed adaptation enables 48% and 50% energy savings for NORDUnet and GEANT network scenario respectively – which is relatively close to the 69% ideal savings given in Fig. 5 (left) for the case that power follows precisely the traffic variation. The reason why in GEANT the savings are slightly higher is given by the efficiency of the MF adaptation.

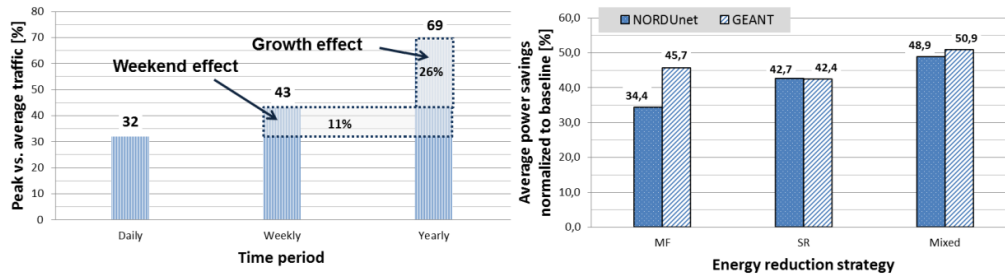


Figure 5. Peak vs. average traffic (left) and average power savings for NORDUnet and GEANT network scenarios (right).

It is important to note that in small foot-print networks (e.g. NORDUnet, for the current comparison) SR adaptation can be deployed without enabling also sleep-mode and/or MF adaptation. In such cases, MF adaptation gains are relatively low and they come at the expense of having a more complex control plane (which requires to always signal the sleep-mode states of the OE devices).

5. Conclusions

Energy consumption represents a significant part of the OPEX associated to NREN operators. Core optical networks can optimize the energy consumption by applying different energy reduction strategies and adapt the energy consumption to the traffic variations thanks to the introduction of elastic opto-electronic devices and sleep-mode approaches. Modulation-format, symbol-rate and the mixed adaptations were proposed and evaluated for NORDUnet and GEANT network scenarios. The results show that up to 50% possible energy savings can be achieved for both networks when Mixed adaptation is deployed. Moreover, MF adaptation is significantly more productive in case of GEANT topology compared to SR adaptation. However, depending on the network – if the footprint is lower and the MF adaptation is less productive, SR-only can be applied in order to allow a less complex control plane.

References

- [1] C. Lange, "Operator perspective on broadband network traffic evolution," in Proc. European Conference on Optical Communications, Amsterdam, Netherlands, Sep. 2012, paper Mo.2.D.1
- [2] O. Gerstel et al., "Elastic optical networking: a new dawn for the optical layer?," Commun. Mag. IEEE, vol. 50, no. 2, pp. S12-S20, Feb. 2012.
- [3] NORDUnet traffic with Customers – Average In traffic for Week 23 2014, <http://stats.nordu.net>
- [4] A. Morea et al., "Power management of optoelectronic interfaces for dynamic optical networks," in Proc. European Conference on Optical Communications, Geneva, Switzerland, Sep. 2011, paper We.8.K.3.
- [5] A. Morea et al., "Data-rate adaptation for night-time energy savings in core networks," J. Lightw. Technol., vol. 31, no. 5, pp. 779-785, 2013.

Biographies

Ioan Turus received his Master of Science in 2011 from Technical University of Denmark, Department of Photonics Engineering. Currently, he is pursuing an industrial PhD program at NORDUnet in collaboration with the same department at Technical University of Denmark. His main interests are advanced control plane architectures for flexible optical networks as well as Software Defined Networks based control planes for optical transport networks. He was involved in the GEANT JRA1 activities and in the Elastic-Optical Networks (EO-Net) Celtic project. Ioan has just returned from a 6 months external stay at Alcatel-Lucent Bell Labs France where he focused on energy efficiency strategies in core optical networks.

Josva Kleist holds a Ph.D. and M.Sc. in Computer Science from Aalborg University. He is coordinating the design and implementation of NORDUnet development projects, internal as well as external. This includes NORDUnet activities within GN3. Josva Kleist joined NORDUnet in 2006 and worked as NDGF Software Coordinator until the end of 2010 and was one of the main drivers behind the Nordic distributed WLCG Tier-1. Josva Kleist came to NORDUnet from Aalborg University where he held a position as associate professor in computer science. His research career has been focused on issues related to networks and distributed systems.

Anna Manolova Fagertun received her M.Sc. in Telecommunications from the Technical University of Denmark in 2006. In March 2010 she obtained a PhD degree in telecommunication technologies from the Department of Photonics Engineering at the Danish Technical University, under the supervision of Professor Lars Dittmann. Her research interests cover diverse aspects of transport networks including transport network control plane technologies, network resiliency and multi-domain/multi-layer integration. Anna has been involved in several national and international research projects: EU NoE BONE; GEANT3; M2R3 (under the Spanish Science and Technology Ministry); "The Road to 100 Gigabit Ethernet", supported by the Danish Advanced Technology Foundation.

G. Evaluation of Flex-Grid architecture for NREN optical networks

Evaluation of Flex-Grid architecture for NREN optical networks

Ioan Turus¹, Josva Kleist¹ and Anna Manolova Fagertun²

1: NORDUnet, Kastruplundgade 22, DK-2770 Kastrup, Denmark, iotu@nordu.net, Phone: +45 31 62 78 17

2: Technical University of Denmark, Copenhagen, Denmark. anva@fotonik.dtu.dk

Keywords

Flex-Grid, GMPLS, control plane, evaluation, Photonic Services

Abstract

The paper presents an in-depth and structured evaluation of the impact that Flex-Grid technology reveals within current NRENs' core optical networks. The evaluation is based on simulations performed with OPNET Modeler tool and considers NORDUnet as well as a normalized GEANT core optical network as reference topologies. Flex-Grid technology is suggested as a solution to cope with the different challenges in NREN transport networks such as traffic increase and introduction of novel physical layer services. Flex-Grid refers to narrow channel spacing values and requires a control plane which would enable all benefits given by the flexible spectrum allocation. GMPLS is considered in our implementation and the simulated scenarios follow the goal of answering the question: Do NRENs benefit from the introduction of Flex-Grid architecture?

1. Introduction to NREN Environment

National Research and Educational Networks (NRENs) represent a particular category of network and service providers which are dedicated to support the needs of the research and education communities within the country they are part of. Because of their particular customer base that poses particular requirements, NREN networks are expected to be leading the technology developments in various areas of the network and service architecture.

There are a number of challenges that currently NRENs are experiencing and the most prominent ones with regards to transport infrastructure can be categorized as follows:

- **Continuously increasing traffic demand:** this is a common aspect for all network providers nowadays and it is determined by two reasons: development of demanding end-user application such as 3DTV, HDTV etc. and fast and wide expansion of novel access network technologies such as FTTH, which enable end-users to use high bandwidths.
- **Heterogeneous aspect of the demands:** traffic demands are currently having very heterogeneous characteristics meaning that parameters such as distance, bit-rate or duration experience high variations. If some years ago these parameters were fairly static, today connections are requested for few km to thousands of km, with bitrates from tens to hundreds of Gbps and lasting from few seconds to semi-permanent ones.
- **Support for novel services:** traditionally NREN environment is required to facilitate the end users to develop and imagine new applications which eventually pose service requirements that cannot be met by standard commercial operators. An example of such service is the Photonic Service (PS) – an all-optical service where a light signal with arbitrary parameters and characteristics is handled by the customer while it is transported completely transparently through the provider's network and handed back to the customer at the receiver as detailed in [1]. The challenge for PS is to be able to provide service isolation via spectrum separation, depending on the type of photonic service used, so that different optical signals can be separated from each other in order to avoid neighboring perturbations in the spectrum.

2. The Flex-Grid concept

The Flex-Grid concept considers the introduction of a lower channel spacing compared to the currently used 50 GHz grid. ITU-T proposed in [2] different channel spacing values such as 25, 12.5 and 6.25 GHz while the lower bound limit of 6.25 GHz was chosen because of the physical limitations and the cost of producing narrow optical filters and Spectrum Selective Switches.

The parameters that describe the Flex-grid architecture are shown in Figure 1 and they define the Central Frequency Granularity (CFG) – the spacing between two consecutive central frequencies, the Spectrum Slice Width (SSW) – the minimum and maximum size of a Spectrum Slice and the Spectrum Slice Granularity (SSG) – the step which gives the possible size values for the Spectrum Slices.

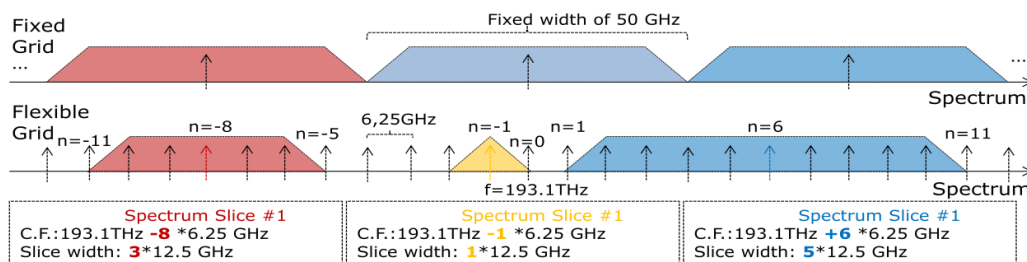


Fig1. Fixed grid vs. Flex-Grid and Spectrum Slice composition in Flex-Grid

3. Use cases and relevance of Flex-Grid for NRENs

There are two main benefits that are expected from the introduction of Flex-Grid to NRENs as opposed to the currently fixed-grid deployments: optimizing the spectrum usage and facilitating introduction of photonic services. A major gain is given by the cost-efficient introduction of novel transmission technologies in the WDM layer. This is due to the fact that high bit-rates will be accommodated in a more cost-efficient way if flex-grid is present. Thus, one big driver is the facilitation of the process of adopting higher bitrates and novel transmission techniques, as well as providing a future-proof WDM infrastructure.

Assuming transponders that are tunable in spectrum are used and every channel is associated with the minimum required amount of spectrum, the assignment of spectrum resources is performed more efficiently. Comparing Figure 1 (top part) and Figure 2, we can observe that for fixed-grid we have only 3 available 50GHz channels in a total of 150 GHz spectrum and whatever three optical channels we want to set-up we will occupy the whole available spectrum. In case Flex-Grid is implemented (see Figure 2), assuming that 1x100Gbps and 2x40 Gbps channels for example are requested – we can manage the spectrum in such a way that we can provide the three optical channels in only 62.5 GHz while leaving the rest of the spectrum for accommodating other services.

Under Photonic Service deployment scenario an effective spectrum isolation can be provided between the Photonic Service slice and the nearest operational optical channel. In this way, not only we optimize the resources for “classical” optical channels but we also facilitate the introduction of photonic services while minimizing costs (avoiding the introduction of new spare capacity or dark fibers).

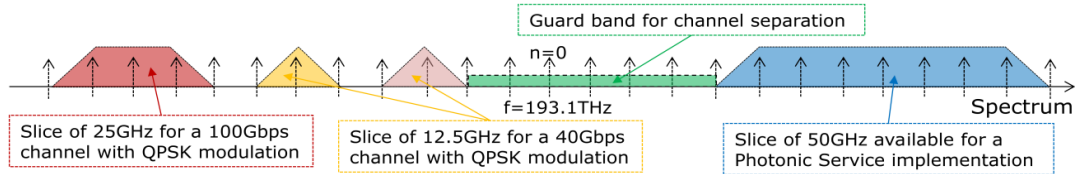


Fig 2. Deployment of optical channels and photonic services in a flex-grid architecture

4. Results and conclusions

At the moment of preparing the extended abstract the GMPLS control plane model is readily available (previous work on this was published in [3]) and is fully operational with different configuration parameters. The NORDUnet and a normalized GEANT fiber print [4] topologies have also been defined in OPNET as shown in Figure 3.

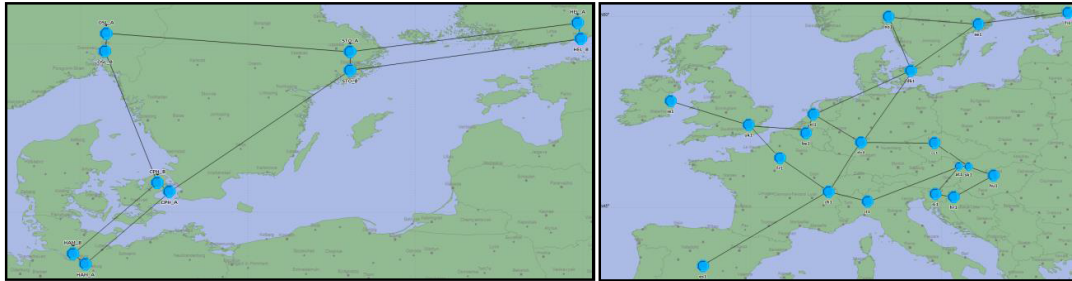


Fig3. NORDUnet (left) and normalized GEANT (right) core optical networks

Simulations are ongoing and the results will target the following aspects:

- Evaluation of potential benefits from introduction of Flex-Grid
 - How much more bandwidth and connections can be served when using flex-grid compared to fix-grid under dynamic connection requests of 40 and 100 Gbps using QPSK modulation?
 - Evaluate the impact on the capacity after the introduction of applications based on Photonic Services (e.g. optical frequency transfer via telecommunications fiber [5])
- Identification of challenges posed by introduction of Flex-Grid
- Comparison between a relatively mesh architecture (GEANT) and a ring-based topology (NORDUnet)
 - What is the difference in efficiency (bandwidth gains, connection blocking) when deploying flex-grid in different topologies?
- Evaluation of the impact of the traffic increase prediction and how this is met by Flex-Grid deployment
 - To what degree NRENs can cope with the traffic increase taking as an example the NORDUnet network where it is estimated an increase from 0.2 Tbps in 2013 to 0.8 Tbps in 2015.

References

- [1] L. L. Bjorn et al., "Photonic Services – Making the Case", GN3 Report, GEANT, July 2013
- [2] ITU-T G.694.1 Recommendation "Spectral grids for WDM applications: DWDM frequency grid"
- [3] I. Turus et al., "GMPLS control plane extensions in support of flex-grid enabled elastic optical networks", OPNETWORK2013, Washington D.C., August 2013
- [4] "Transforming the way researchers collaborate – The pan-European network with global capabilities", GEANT Brochure, www.geant.net
- [5] G. Groche et al., "Optical Frequency Transfer via telecommunication fibers", International workshop "Optical Networks for Accurate Time and Frequency Transfer", EMRP-project NEAT-FT, November 2012

Vitae

Ioan Turus received his Master of Science in 2011 from Technical University of Denmark, Department of Photonics Engineering. Currently, he is pursuing an industrial PhD program at NORDUnet in collaboration with the same department at Technical University of Denmark. His main interest is Software Defined Networks and OpenFlow as well as control plane architectures for elastic optical networks. He is also involved in the GEANT activities and in the EO-Net Celtic project.

Josva Kleist holds a Ph.D. and M.Sc. in Computer Science from Aalborg University. He is coordinating the design and implementation of NORDUnet development projects, internal as well as external. This includes NORDUnet activities within GN3. Josva Kleist joined NORDUnet in 2006 and worked as NDGF Software Coordinator until the end of 2010 and was one of the main drivers behind the Nordic distributed WLCG Tier-1. Josva Kleist came to NORDUnet from Aalborg University where he held a position as associate professor in computer science. His research career has been focused on issues related to networks and distributed systems.

Anna Manolova Fagertun received her M.Sc. in Telecommunications from the Technical University of Denmark in 2006. In March 2010 she obtained a PhD degree in telecommunication technologies from the Department of Photonics Engineering at the Danish Technical University, under the supervision of Professor Lars Dittmann. Her research interests cover diverse aspects of transport networks including transport network control plane technologies, network resiliency and multi-domain/multi-layer integration. Anna has been involved in several national and international research projects: EU NoE BONE; GEANT3; M2R3 (under the Spanish Science and Technology Ministry); "The Road to 100 Gigabit Ethernet", supported by the Danish Advanced Technology Foundation.

H. Evaluation of Distributed Spectrum Allocation Algorithms for GMPLS Elastic Optical Networks

Evaluation of Distributed Spectrum Allocation Algorithms for GMPLS Elastic Optical Networks

Ioan Turus, Josva Kleist
NORDUnet A/S
DK-2770 Kastrup, Denmark
{iotu, kleist}@nordu.net

Anna Manolova Fagertun, Lars Dittmann
Department of Photonics Engineering
Technical University of Denmark
DK-2800 Lyngby, Denmark
{anva, ladit}@fotonik.dtu.dk

Abstract—Elastic Optical Networks (EO-Net) represent a novel approach that allows a better utilization of the optical resources by providing a higher flexibility and a better assignment of capacity for every specific traffic demand or network state. One of the key requirements for enabling elasticity in the network is to provide a control plane capable of handling the elastic parameters and elastic connections. Towards this direction, in this paper, we assess the performance of different algorithms for spectrum allocation based on extended RSVP-TE protocol with focus on the signaling procedure. The evaluation is performed by implementing RSVP-TE extension in a flex-grid model using OPNET modeler. Finally, we propose and test improved solutions for reducing the percentage of blocked connections with up to 10% as well as achieving a 50% lower spectrum fragmentation.

Keywords—elastic optical networks; GMPLS; flex-grid.

I. INTRODUCTION

The growth of network traffic represents a main factor which drives the development of novel optical networks technologies. Nowadays optical networks employ a very rigid deployment of resources which faces a constant increase of traffic of around 2dB per year [1]. This challenge cannot be sustained by the development of optical network technology which provides a gain in capacity of less than 1dB per year according to [2]. Thus, it becomes clear that network capacity tends to become a future bottleneck.

There are several ways to cope with this issue and meet the required capacity demands of the clients. One way is to add more channels (wavelengths) on a single fiber. This is a good solution as long as there is spectrum available in the fiber, since for instance in the C band a maximum number of 80 channels at 50 GHz channel spacing can be accommodated. Once this limit is reached, a new fiber is required. Adding more fibers is another solution to increase the capacity. However, this is difficult to realize due to the fact that fiber installation is an expensive operation and usually a fixed, rather small, number of fibers are provided and are available to be used on a certain path.

Another common solution is to increase the capacity of the individual channels in the fiber employing advanced modulation formats that can provide higher bitrates. However, this approach limits the maximum transmission reach making

this option efficient only when providing higher capacities over short distances. This is due to the fact that in long distances regeneration is required and the cost of the provisioning increases accordingly.

A natural improvement towards provisioning of optical networks capacity is to add a higher degree of flexibility or elasticity in the parameters of the optical connection. The advantage of having flexible optical networks is the ability to assign capacity in strong correlation with the property of every demand. In this way, capacity will not be overprovisioned and more traffic could be accommodated in the present deployed infrastructure.

Elastic Optical Networks (EO-Net) requires a number of novel technologies and elements in order to provide the proposed flexibility. An important enabling technology is the development of a flexible transponder which is able to adjust the bitrate according to the demand. Also, the parameters of the optical connection such as modulation format, Forward Error Correction (FEC) codes and the assigned amount of spectrum have to permit flexible choice per individual connection.

The focus of this paper is the flexible assignment of spectrum resources in an elastic optical network, also called Flex-Grid network. Flex-Grid comes as an idealistic improvement of the Fix-Grid standard defined by ITU-T [3] which defines a 50GHz spectral granularity for each optical channel. Flex-Grid proposes to narrow down the minimum amount of spectrum that can be assigned to one connection making it variable in order to fit to the precise requirement of the transponder. ITU-T is currently proposing a flex-grid standard in the edition 2.0 of [3] which defines Spectrum Slots (SSs) that are placed at a distance of 6.25 GHz and which can be combined to create a more flexible spectrum channel.

A significant amount of research effort is dedicated to the area of flex-grid optical networks to investigate the minimum amount of spectrum that can define a Spectrum Slot in order to minimize the blocking of connections in the network or to analyze the performance for different spectrum granularities according to the served connections [4].

Another key factor to enable elasticity in optical networks particularly in the functions of flex-grid is to deploy a control plane which is able to handle the new parameters and functions in an efficient manner. The work in [5] proposes GMPLS and

OpenFlow extensions for handling flex-grid connections while [6] is looking into novel methods for improved routing and wavelength or spectrum slots assignment for the GMPLS control plane.

This paper investigates GMPLS as control plane for elastic optical networks with a distributed control, opposed to the solutions proposed so far that use a Path Computation Element [6]. In particular, this work focuses on the different schemes for assigning spectrum slots for an elastic optical connection while using a standard Dijkstra shortest path algorithm for the routing component. The remainder of this paper is organized as follows: In Section II the flex-grid architecture and the control plane based on GMPLS are presented. In Section III the proposed and the investigated spectrum allocation methods are shown. In Section IV the simulation setup is presented. Sections V and Section VI provide the results and conclude the paper respectively.

II. FLEX-GRID

A. Flex-Grid architecture

Flex-Grid represents the advanced spectrum division proposed by ITU-T [3] in order to increase the flexibility of spectrum allocation in optical networks. The standard specifies different values of the distance between two channels or the bandwidth of a single channel. Nevertheless, there are still limitations from the physical elements which need to be able to filter or switch (Bandwidth-Variable Wavelength Selective Switches) these narrow channels.

Contrary to the simplicity of the standard fix-grid way of assigning channels and having a wavelength identifier for every available and static channel in a fiber, flex-grid networks require more parameters in order to identify and define a flexible channel.

We refer to a flexible channel in flex-grid network as Spectrum Slot (SS) or slice, which can have a variable or flexible size. A particular case for the Spectrum Slot is the Elementary Spectrum Slot (ESS) which is equivalent to the distance between two central frequencies.

In order to define a flex-grid optical channel and represent it in the control plane functionality, the following parameters shown in Fig. 1, are required:

- Central Frequency Granularity (CFG) – represents the distance between two consecutive central frequencies.
- Spectrum Slot Granularity (SSG) – specifies the minimum value that a Spectrum Slot can get as well as the step which defines the higher values for the Spectrum Slots.
- “n” value - represents the central frequency of the spectrum slot. It is computed based on the nominal frequency of the C band (193.1 THz) and the positive or negative index of the central frequency from the grid.
- “m” value – represents the number of Elementary Spectrum Slots that are grouped in one side of the central frequency of the spectrum slot.

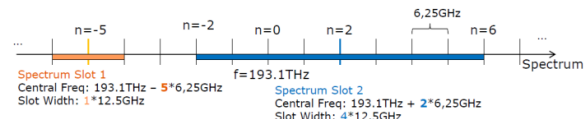


Fig. 1. Flex-Grid channel parameters.

For example in Fig. 1, for spectrum slot number 1, the central frequency is calculated as a negative shift of 5 positions in the grid while in case of spectrum slot number 2 the central frequency is a positive shift of 2 positions from the nominal central frequency. Furthermore, there are two ESSs that form Spectrum Slot 1 so the “m” parameters is 1, while in case of Spectrum Slot 2, the width of the spectrum is 4 ESS in each side and the value for the “m” parameter is 4.

ESS represents the unit which is multiplied to form a Spectrum Slot. In case of defining a channel for every single central frequency in a fiber, the Elementary Spectrum Slots (ESSs) are created – representing Spectrum Slots of CFG assigned amount of spectrum. In Fig. 1 the CFG is 6.25 GHz.

The ESS cannot be a valid channel by itself in the GMPLS control plane because of the definition of a channel given by the “n” and “m” parameters and which requires a minimum value for m to be 1. In this case, the minimum spectrum slot that can be assigned is the double of the ESS.

Associating these definitions to the fix-grid case it can be said that the equivalent of a wavelength index in fix-grid networks is the “n” and “m” pair in flex-grid networks.

B. GMPLS Control Plane for Elastic Optical Networks

Previous works in the field of GMPLS extensions for flex-grid control plane are presented in [5, 6] and rely on centralized architecture. In our work we adopt a distributed architecture and each source node has its own routing, path computation and signaling engines.

In GMPLS, OSPF-TE is responsible for disseminating the spectrum information by extending the OSPF-TE LSAs to accommodate the Spectrum Slot representation. The effect of the OSPF-TE routing on improving the path computation is out of the scope of the present work, thus we adopt a standard Dijkstra shortest-path algorithm. In this way, the different spectrum assignment methods that are investigated can be compared and evaluated without quantifying the influence or improvement given by the routing.

Signaling in GMPLS networks is performed by RSVP-TE which is responsible of reserving the resources along the chosen path. RSVP-TE is using the Label Set object to collect at every node it passes along the path all available central frequencies which can fit the requirement from the spectrum slot size. A central frequency is considered available if it has the required number of Elementary Spectrum Slots available on both sides of the central frequency on the outgoing port.

Compared to a classical fix-grid network, in our case the Label Set object includes generalized labels, instead of wavelengths labels, and the PATH message also carries the “m” parameter which defines the required spectrum amount.

The focus of this paper is towards the distributed way of assigning the spectrum and towards the different methods that can be used at the destination to select one central frequency which determines the lowest possible blocking and highest usage of resources in the network. Some of the methods that are evaluated are taken from the fix-grid or WDM networks and they are studied in depth, e.g. First-Fit and Random Assignment, while others are proposed specifically for flex-grid spectrum allocation, as the solution presented in [6].

III. SPECTRUM ALLOCATION METHODS

A. Classic label allocation methods

Even though Wavelength Assignment methods applied in fix-grid WDM networks can be also applied to flex-grid networks, their efficiency is expected to be different because of the granularity and the fragmentation that are characteristic of flex-grid networks. The following spectrum assignment methods are evaluated in our work:

- FF:

The First-Fit algorithm is one of the default methods used to select a resource out of an arranged pool of resources.

- RA:

Random Assignment algorithm is a method where instead of packing the resources in one side of the pool (as FF), it tries to randomly spread them around the pool.

- Mixed-Fit:

The Mixed-Fit algorithm uses the benefit of First-Fit but instead of packing resources in one side of the spectrum it implements a mixed FF and Last Fit strategy which effectively packs the resources on both sides of the spectrum.

B. Proposed novel spectrum allocation schemes

Apart from the already existing allocation schemes, we suggest two novel ones targeting to improve the blocking in the networks as well as the resulted spectrum fragmentation.

- SSbalanced

SSbalanced algorithm differentiates the connections based on the number of spectrum slots they request by using a limit parameter which is referred when deciding whether to use either the First-Fit or the Last-Fit allocation scheme. As an example, if the SSbalanced limit is 5, all connections requiring 5 or less elementary spectrum slots will be assigned as First-Fit, while the ones with more than 5 ESSs will be assigned as Last-Fit.

- Metric balanced LP

We call Metric Label Preference the implementation of the method proposed in [6] where the number of “empty” gaps before or after a Spectrum Slot is computed for every central frequency on every link along the path, while the destination node chooses the Spectrum Slot based on the central frequency with the highest number of empty gaps. In the implementation of [6], in case of ties, First-Fit is used to choose between them.

Metric balanced Label Preference is our proposal for extending the method based on Metric LP with the difference that instead of solving the ties with First-Fit, the SSbalanced mechanism proposed above is used.

IV. SIMULATION SETUP

We evaluate the performance of the spectrum assignment schemes in a COST 266 network model as shown in Fig. 2.

The input traffic load is varied between 10 and 25 Erlangs per node, with a fixed connection duration time of 4.5 h while the traffic arrival follows a Poisson distribution. The chosen input traffic guarantees operation below 10% blocking in the network shown in Fig. 2. It is assumed that every node has elastic transponders working at 4 bitrates: 25, 50, 75 and 100 Gbps as proposed in [7]. Every bitrate has a probability of 25% to be generated. We also consider that 1 bit per symbol is used so the spectrum required for every connection is simplified and will be among 25, 50, 75 and 100 GHz.

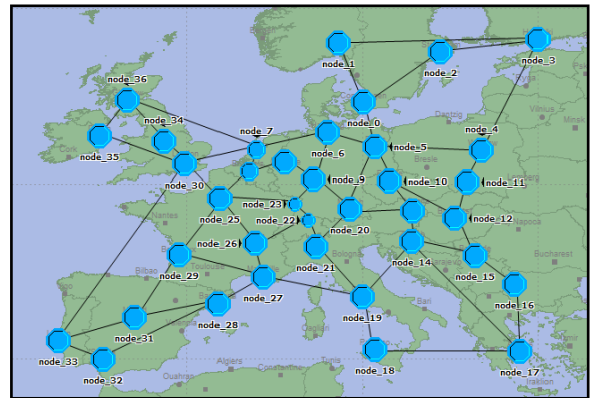


Fig. 2. Network architecture modeled in OPNET Modeler [8].

A. GMPLS implementation

In order to be able to handle Spectrum Slots, RSVP-TE was extended to allow carrying of generalized label definition as shown in [9] as well as the “m” parameter. The generalized labels or available central frequencies are carried in the Label Set Object, while the “m” parameter is carried in the *Tspec* object without any changes from source to destination.

We evaluate the spectrum assignment methods based on the following two performance measures:

- Blocking percentage – indicates the amount of blocked connection requests in the network
- Fragmentation – indicates the number of islands (or gaps) of specific size

Whenever a Spectrum Slot is reserved, there is a possibility that after and/or before an island (or gap) can be created. If this gap is only 1 free ESS then the gap is unable to serve any new connection request which indicates loss of spectral efficiency.

B. Flex-Grid implementation

The CFG value used for the current simulations is 12.5 GHz which determines that 320 Elementary Spectrum Slots, out of the total 4 THz optical spectrum, will be available on every link. The SSG value chosen for the investigated scenarios is 12.5 GHz which means that Spectrum Slots with the size of 12.5, 25, 37.5, 50 GHz etc can be created.

Based on the CFG and SSG values, the required number of Spectrum Slots can be computed for the four types of demands generated by every node. In case of incoming bitrate of 25 Gbps, the smallest amount of spectrum that can be assigned is 25 GHz (a Spectrum Slot with 2 times the size of SSG) and knowing that one ESS is 12.5 GHz, it means that the 25 Gbps is assigned a Spectrum Slot made by 2 ESSs. In a similar manner, the demands with 50 Gbps will be assigned a Spectrum Slot of 4 ESSs, the 75 Gbps demands will require 6ESSs while the 100 Gbps demands will require 8 ESSs.

It is important to note that every assigned Spectrum Slot has an even number of assigned ESSs and this is due to the way flex-grid specifies a Spectrum Slot, with the “n” and “m” pair where “m” represents the width in ESSs at both left and right side of the central frequency (“n”) and determines always having an even number of ESSs in a Spectrum Slot.

V. SIMULATION RESULTS

First, we investigate the performance of the classical label assignment methods. Afterwards the proposed SSbalanced and Metric balanced LP methods are verified in terms of limit parameter. Finally, the methods are compared in terms of blocking and fragmentation. From the fragmentation perspective the number of smallest gaps (of 2ESSs) is computed as an average made over the total number of established elastic connections.

A. Classic label allocation methods evaluation for flex-grid

First-Fit, Random Assignment and Mixed-Fit methods are compared in terms of blocking percentage and the results are shown in Fig 3. It can be observed that the blocking is significantly higher for the Random Assignment method and this is due to the fragmentation created by the variable Spectrum Slot size. Mixed-Fit shows also a significantly higher blocking percentage in comparison with First-Fit.

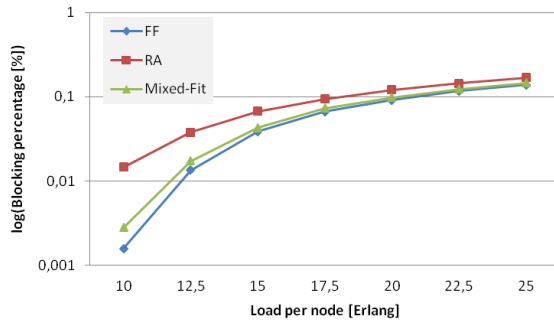


Fig. 3. Blocking percentage for FF, RA and Mixed-Fit.

Out of the classical spectrum assignment methods First-Fit outperforms both RA and Mixed-Fit methods in terms of blocked connections. For this reason, we will refer to First-Fit further on as a reference for comparison with novel methods.

B. SSbalanced evaluation

The evaluation of the SSbalanced method takes into account the number of Elementary Spectrum Slots which form a certain Spectrum Slot and their shift to one of the sides of the spectrum depending on the chosen *SSbalanced limit*. According to Fig 4, the blocking percentage is not changed to a significant degree by the variation of the SSbalanced limit parameter, with respect to the First-Fit result.

The main improvement in SSbalanced comes from the fragmentation perspective, where according to Fig 5, the number of islands of 2ESS free is in average lower than the case of First-Fit. For the best choice, of SSbalanced limit equal to 7 (only Spectrum Slots made of 8 ESSs are assigned with Last-Fit strategy while the rest with First-Fit) it can be observed an improvement of 25% in terms of fragmentation. The trend is also valid for higher size gaps (e.g. 4 or 6 ESSs).

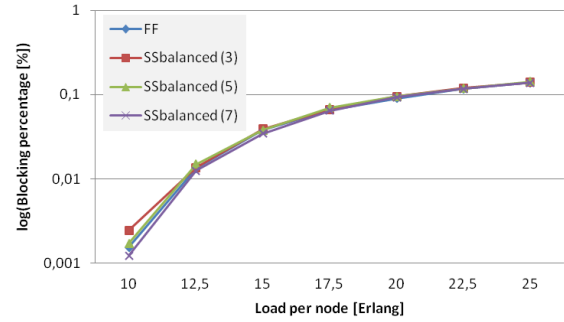


Fig. 4. Blocking percentage for different SSbalanced thresholds.

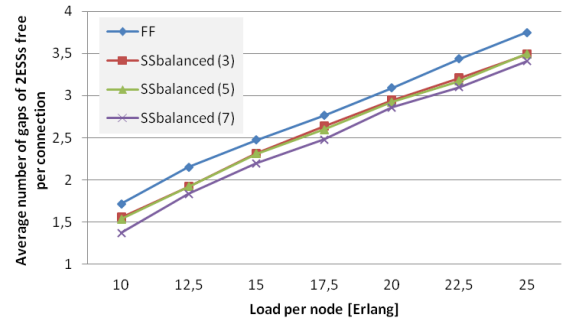


Fig. 5. Average number of gaps of 2ESS free per connection for different SSbalanced thresholds.

We conclude that the best choice for the SSbalanced parameter is to isolate the connections with the highest number of ESSs in one side of the spectrum while leaving the remaining ones in the other side.

C. Metric balanced LP evaluation

We propose Metric balanced LP method as an improvement for the Metric LP where instead of using FF for handling ties we use SSbalanced with a limit of 7. The blocking percentage remains unchanged while the improvement our method brings towards Metric LP is towards fragmentation as depicted in Fig. 6. The results of the simulation in our network show that Metric balanced LP with a limit of 7 ESSs leaves up to 8% less empty gaps on average, depending on the load in the nodes.

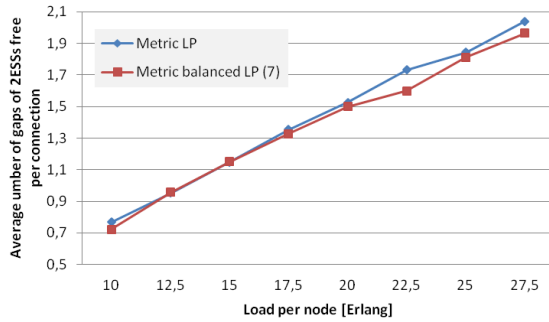


Fig. 6. Average number of gaps of 2ESS free per connection for Metric and Metric balanced LP (7).

D. First-Fit, SSbalanced and Metric balanced LP evaluation

We evaluate the two proposed methods: SSbalanced and Metric balanced LP in their most effective configuration and we compare them with the First-Fit algorithm. Fig. 7 shows blocking is very similar for all of the 3 analyzed methods with the exception that for less loaded nodes SSbalanced is able to provide up to 10% less blocking.

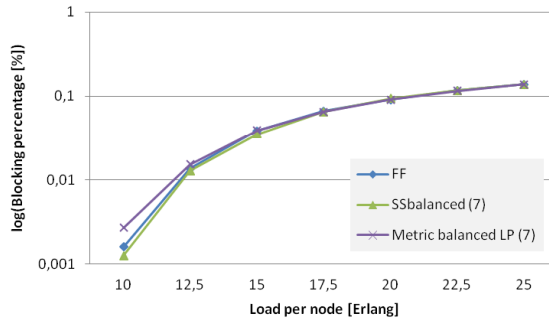


Fig. 7. Blocking percentage for FF, SSbalanced and Metric Balanced LP.

The main difference and improvement that the proposed method brings is related to fragmentation. As shown in Fig. 8, First-Fit provides the worse fragmentation or the highest number of empty gaps. SSbalanced provides a significantly lower fragmentation (up to 10% less gaps) while Metric balanced LP (7) decreases the number of empty gaps with up to 50% compared to the First-Fit case.

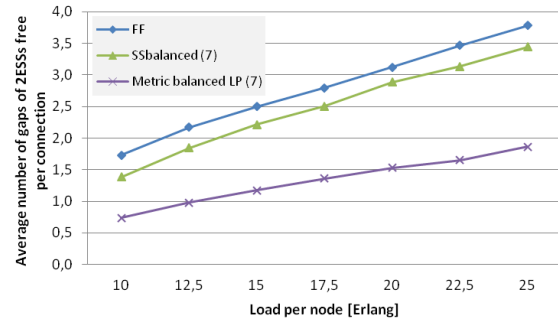


Fig. 8. Average number of gaps of 2ESS free per connection for SSbalanced and Metric balanced LP (7).

VI. CONCLUSIONS

We investigated different distributed spectrum assignment algorithms for the flex-grid elastic optical networks using GMPLS control plane. Routing aspects were neglected in order to emphasize the role of the spectrum allocation algorithms and extensions for RSVP-TE were implemented in order to handle flex-grid parameters. Classic label allocation methods used also in fixed-grid networks were evaluated and First-Fit is found to outperform the rest for assigning spectrum in flex-grid networks in terms of blocking.

Novel allocation methods were proposed showing that simple mechanisms such as SSbalanced can reduce fragmentation with up to 10% while for low loads the blocking can be reduced as well with up to 10%. Despite increased complexity, Metric balanced LP gives the best results in terms of fragmentation which is reduced with up to 50% while the blocking is similar with the First-Fit case.

References

- [1] R. W. Tkach "Scaling optical communications for the next decade and beyond" Bell Labs Technical Journal, vol. 14, no. 4, pp. 3 – 9, Feb. 2010
- [2] R. J. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, B. Goebel "Capacity limits of optical fiber networks," *J. Lightw. Technol.*, vol. 28, no. 4, pp. 662 – 701, Feb. 2010
- [3] ITU-T G.694.1 Recommendation "Spectral grids for WDM application"
- [4] X. Wang, Q. Zhang, I. Kim, P. Palacharla, M. Sekiya "Blocking performance in dynamic flexible grid optical networks – what is the ideal spectrum granularity" in *Proc. 37th Eur. Conf. Opt. Commun.*, Geneva, Switzerland, Sept. 2011, pp. 1-3, Paper Mo.2.K.6
- [5] L. Liu, R. Casellas, R. Martinez, R. Munoz "Control plane techniques for elastic optical networks: GMPLS/PCE vs OpenFlow," *IEEE Globecom*, pp. 352 – 357, Saitama, Japan, Dec. 2012
- [6] R. Munoz, R. Casellas, R. Martinez "Dynamic distributed spectrum allocation in GMPLS-controlled elastic optical networks," in *Proc. 37th Eur. Conf. Opt. Commun.*, Geneva, Switzerland, Sept. 2011, pp. 1-3, Paper Tu.5.K.4
- [7] A. Morea and O. Rival "Efficiency gain from elastic optical networks," in *Proc. SPIE 8309, Optical Transmission Systems, Subsystems, and Technologies IX*, 83091P, Dec. 2011, doi:10.1117/12/900445
- [8] OPNET Modeler, OPNET Technologies, <http://www.opnet.com>
- [9] D. King, A. Farrel, Y. Li, F. Zhang, R. Casellas, "Generalized labels for the Flexi-Grid in Lambda-Switch Capable (LSC) Label Switching Routers", IETF draft, 2013

I. Spectrum defragmentation based on Hitless Network Re-Optimization with RSVP-TE in GMPLS-based Flexible Optical Networks

Spectrum defragmentation based on Hitless Network Re-Optimization with RSVP-TE in GMPLS-based Flexible Optical Networks

Ioan Turus¹, Anna Manolova Fagertun², Josva Kleist¹, Lars Dittmann²

¹NORDUnet A/S, Kastrup, Denmark 2700, Email: {iotu, kleist}@nordunet

²Technical University of Denmark, Kgs Lyngby, Denmark 2800, E-mail: {anva, ladit}@fotonik.dtu.dk

Abstract—Flex-Grid based Optical Networks are currently seen as a solution for providing higher capacity in contemporary transport networks while also coping with the increasing dynamicity of the traffic demands. Flex-grid design comes with the drawback of creating fragmentation in the spectrum which causes inefficient usage of the grid. We propose a hitless network re-optimization approach using a modified RSVP-TE refresh procedure in order to improve the deployment of channels in the flexible grid. Improvements in connection blocking probability can be observed by applying our proposed extension to the RSVP-TE refresh process under a distributed GMPLS control plane framework.

Index Terms—defragmentation, flex-grid, GMPLS, hitless, re-optimization, RSVP-TE

I. INTRODUCTION

Network operators are facing today various challenges when deploying or upgrading their core optical network infrastructure. Ongoing changes are needed due to the continuously increasing capacity demand, of about 2dB per year [1]. Moreover, the heterogeneous behavior of the traffic demands is adding another degree of complexity to the optical network design. There is a need to provide connections which have a significant variation in bandwidth, time and/or distance and this requires a more flexible control plane as well as a highly intelligent assignment of resources.

One way to cope with these challenges is to enable a more efficient assignment of optical capacity for the traffic demands. Currently, WSON (Wavelength Switched Optical Networks) architecture specifies a 50GHz fixed channel spacing when deploying optical channels and it is the de-facto standard among network providers. Recent extensions to the ITU-T's grid specification [2] propose a narrower grid which defines lower values for the channel spacing in the spectrum. The channel spacing is decreased down to 6.25 GHz and so called Spectrum Slots are defined as the smallest unit in the spectrum grid. A number of contiguous spectrum slots can be grouped together to form a spectrum slice which is the equivalent of the today's 50GHz channel with the difference

that it is flexible in size and position. Such networks are referred to as Spectrum Switched Optical Networks (SSON, [3]) or flex-grid networks.

The newly deployed flex-grid network architectures require intelligent control in order to handle automatic set-up, reconfiguration and tear down of connections. Generalized MultiProtocol Label Switching (GMPLS) architecture is proposed as a solution for enabling the flexible attributes of the channels in SSON, where required extensions are currently being defined for both the OSPF-TE and the RSVP-TE protocols [4], [5], [6].

The deployment of flex-grid channels comes with the expense of causing fragmentation of the spectrum grid, as described in [7]. This is due to the fact that dynamic connections are allocated variable slice sizes on different paths and gaps are created between the reserved spectrum slots.

In order to reduce the fragmentation of the spectrum on the links along a path in the network, the control plane is required to re-allocate the connections in such a way that spectrum gaps are minimized and the spectrum is arranged in a more compact way. There are two options for doing the re-allocation of the spectrum assigned for the optical channel: one option is to apply Make-Before-Break [8] techniques while the other one is to re-assign the channel in a neighboring position over the same links in the path, namely hitless procedure. The first procedure is not preferable for dynamic optical networks because it assumes the assignment of the connection on a different route and the traffic transition from old to the new route can be traffic disruptive. On the other hand, the hitless procedure assumes a push-and-pull approach [9] which is based on the re-allocation of the channel on the same path to a neighboring position which forms a contiguous spectrum slice together with the currently reserved spectrum. The advantage of the hitless re-optimization approach is that it enables the source laser to re-tune its operating frequency to a neighboring frequency value while the traffic perceives this process transparently.

Previous work [9], [10] and [11] has been done on proposing or enabling hitless de-fragmentation. In [11] the benefit of running OSPF-TE is taken into consideration and the information about the slot status from all links in the network is gathered. Based on this information, a channel can

be re-allocated in a better position for minimizing the fragmentation. The decision is taken by the source node of the connection and suggested labels are used in order to signal the new resources towards the destination.

The work in this paper counteracts the possible drawbacks of running OSPF-TE advertisements in flex-grid networks such as: delayed slot status information and high load in the control plane due to excessive message exchange. By extending the RSVP-TE refresh procedure our proposal gathers the information about spectrum availability along the path of a connection in a distributed manner without advertising link status information for all links in the network to spectrum databases. Furthermore, the information is available much faster than in case of using OSPF-TE because it does not need to converge in all the nodes in the network.

The remainder of this paper is organized as follows: In Section II the RSVP-TE refresh procedure and the hitless re-optimization technique based on RSVP-TE are detailed. In Section III the used simulation setup for performance evaluation is described. Section IV presents the results and their analysis. Section V concludes the paper.

II. RSVP-TE REFRESH-BASED HITLESS RE-OPTIMIZATION PROCEDURE

In our work we adopt a distributed architecture based on GMPLS where each source node has its own routing, path computation and signaling engines. In GMPLS, OSPF-TE is responsible for disseminating spectrum information by extending the OSPF-TE Links State Advertisements (LSAs) to accommodate the spectrum slot representation. However, in this work OSPF-TE is not used for slot status advertisements. This is done in order to have a lighter control plane and prove the RSVP-TE based defragmentation approach. The reason behind running defragmentation based on RSVP-TE is that OSPF-TE is required to advertise the status information of a high number of slots that are changing their status. In this case, the approach of using information advertised with OSPF-TE is facing a trade-off between the periodicity of the broadcasted advertisement and the freshness of the information received in one node from the neighboring nodes.

Signaling in GMPLS networks is performed by the RSVP-TE protocol which is responsible of managing (reserving, maintaining and decommisioning) the resources along the path chosen for a given connection.

A. RSVP-TE Refresh

According to [12], RSVP is a soft-state protocol, i.e., it creates a soft-state which is periodically refreshed by PATH and RESV messages in order to manage the reservation state in network nodes. In case of no received refresh messages before the expiration of a timer, the state is deleted and the connection enters a tear down process. Every refresh PATH and RESV messages contain a TIME_VALUES object where the timer used to generate the refresh messages is stored.

The difference between a set-up or refresh PATH/RESV messages is to be decided at every node depending upon the existence of a soft-state, i.e., if a soft-state already exists for

the current connection, the current PATH/RESV message and the following ones are considered refresh messages.

The RSVP-TE PATH message (used for connection establishment as well as for connection status refresh) uses a Label Set object to collect at every node it passes along the path all available central frequencies which can satisfy the requirements of the connection from spectrum slot size perspective. A central frequency is considered available if it has the required number of spectrum slots available on both sides of the central frequency on the outgoing port. Compared to a classical fix-grid network, the Label Set object includes generalized labels instead of wavelengths and the PATH message carries a parameter which defines the required spectrum amount as well.

In optical transport networks under GMPLS control plane it is desirable the RSVP refresh process to be suspended. This is done in order to facilitate a full isolation between the data plane and the control plane, for increased resiliency to control plane failures and for avoiding disruptions of perfectly functioning data plane connection under control plane failures. In this work we use the refresh process as a means for re-optimization, i.e., if a refresh message is not received in due time we do not decommision the connection.

B. Hitless re-optimization procedure based on RSVP-TE

The hitless re-optimization technique proposed in this paper is incorporated within the RSVP-TE refresh procedure. Once a connection needs to be established, a path is computed using a standard Dijkstra algorithm and resources along the path are reserved by the RSVP-TE protocol. We make use of the soft-state behavior of the RSVP-TE in order to verify the availability of the resources which could enable a re-optimization of the connection on the current path. Thus, we use refresh messages with the role of re-optimization and not for keeping alive the state of a connection. The actual main benefit of the refresh messages used in the current implementation is to be able to periodically check the link for resources availability as well as reserving and tearing down resources when a re-allocation can take place.

Thus, we configure a timer which triggers a refresh message exchange for the already established connection. Once the timer expires, a refresh PATH message is sent along the path to verify the availability of the resources or to notify about the release of unused resources. A refresh RESV message is sent upstream to the source in order to reserve, when required, new spectrum resources after the PATH successfully reaches the destination. The refresh timer is chosen as a trade-off value which takes into consideration the fact that a too low value could determine a high dynamicity in shifting connections which can be inefficient for decreasing connection blocking while a value that is too high would not benefit enough of all the situations available for performing a shift.

The main advantage of employing the RSVP-TE refresh procedure is that it only adds small changes in the protocol functionality, while it remains compatible with the common behavior of RSVP-TE. Moreover, the RSVP-TE refresh messages are able to provide up-to-date information about the status of the resources along the path corresponding to the connection under handling.

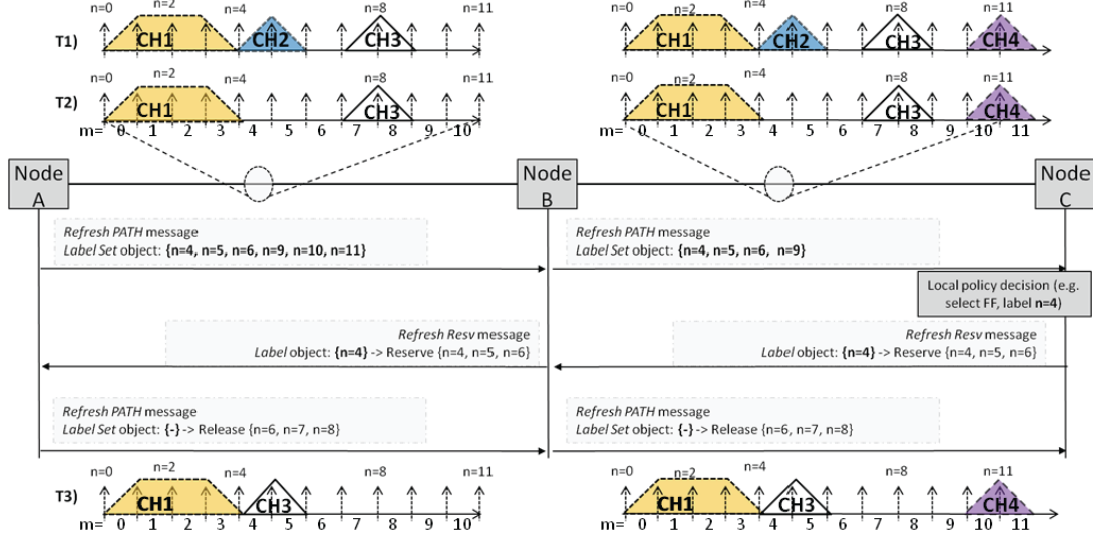


Fig 1. RSVP-TE Refresh message exchange for re-optimization procedure

The proposed distributed hitless re-optimization procedure as well as the flow of RSVP-TE refresh messages is described in Figure 1. The value n represents the central frequency which can be assigned to a spectrum slice while m refers to the spectrum slot number.

After a connection is successfully established, a refresh timer is initiated. Upon its expiration the refresh procedure is executed as follows. The figure illustrates the states of two links at time T1 (initial state) and at time T2 where CH2 connection is released while the CH4 connection has just been set-up. This change results in an increased fragmentation in the two links. After time T2 passes, it will be beneficial to shift the CH3 connection to the left next to CH1.

In order to be able to re-allocate CH3 a refresh PATH message travels from A to C via B and identifies spectrum slots 4, 5 and 6 to be free on both links. Node C takes a decision based on a local policy – in this case a First Fit policy, to choose to shift the CH3 connection to frequency $n=4$. Thus, a RESV message returns from node C to node A reserving all the frequencies between the chosen one and the current position of the CH3 connection. The reason behind reserving this large slice is to allow the laser to re-tune to the new position without disruptions, on a contiguous chunk of spectrum.

Once the refresh RESV message reaches the source node and spectrum slots from $m=4$ to 8 are all reserved, the laser can re-tune to the central frequency of the new slice ($n=5$). Afterwards, another refresh PATH message is sent from source to destination with the purpose of informing the nodes along the path to release the unused frequency slots.

This procedure is repeated whenever the refresh timer expires and the ultimate goal is to be able to pack the channels with a First-Fit policy and release chunks of spectrum on the right side of the spectrum.

III. SIMULATION SETUP

We evaluate the performance of the proposed RSVP-TE based hitless re-optimization via simulations, conducted with the event-driven simulator OPNET Modeler [13]. We apply the mechanism in two standard network scenarios: a 17 node German network and the NSFnet as shown in Figure 2.

The input traffic load for every node is varied between 25 and 50 Erlangs for the 17 node German network and between 50 and 75 Erlangs for the NSFnet network. The choice for the tested load values was made in order to obtain similar connection blocking percentages of around 1% to 10% in both scenarios. It is assumed that every node is able to request connections varying between {4, 7, 10, 12} spectrum slots (in 6.25 GHz grid) and they are uniformly distributed, thus having a probability of 25% to generate each of the 4 demands.

The mean inter-arrival time (MIT) of the incoming demands is exponentially distributed with a mean value of 900 seconds while the duration is computed by taking into account the load per node value.

From the flex-grid design perspective, 640 slots per link are defined, which is equivalent to 6.25 GHz channel spacing. The refresh timer for the RSVP-TE refresh messages is configured at 3600 seconds.

We evaluate the performance of the re-optimization method by measuring the percentage of blocked connections as well as the number of re-optimizations that are performed on average per connection which is re-optimized at least once. The number of blocked connections is referred as a percentage of connections that are blocked in the set-up process, out of the total number of generated connections.

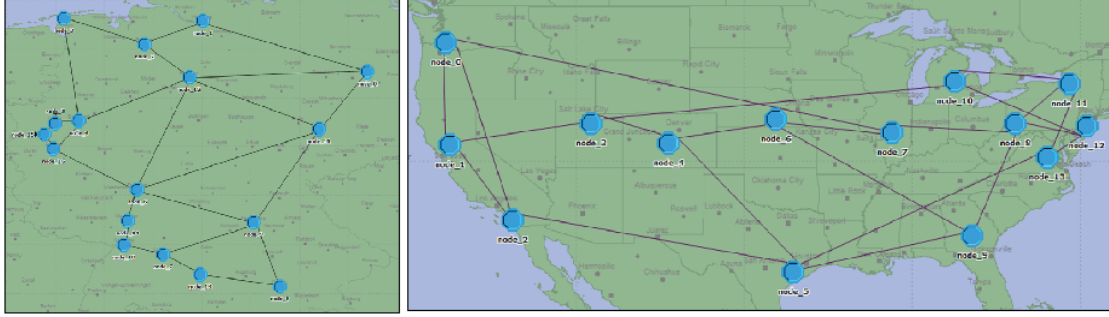


Fig 2. Reference topologies for German 17 nodes network (left) and the NSFnet network (right)

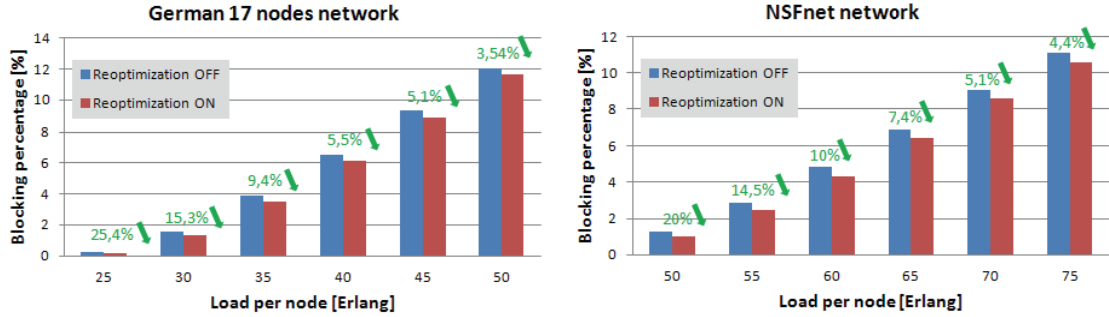


Fig 3. Connection blocking percentage for the German 17 nodes network (left) and the NSFnet network (right)

IV. RESULTS AND DISCUSSIONS

The percentage of blocked connections in the two reference networks is shown in Figure 3. It can be observed that for similar level of blocking (between 1% and 10%) the NSFnet network is able to handle a higher load and this can be explained by a higher nodal degree in the case of NSFnet topology. In both cases the re-optimization procedure was applied for re-allocating connections and reducing fragmentation. The results show that depending on the input load, the blocking can be reduced with 3% to 25% for the German network and between 4% and 20% for the NSFnet network.

Moreover, it can be observed in Figure 3 that the efficiency of the re-optimization procedure, expressed as percentage of improved blocking, is higher when the input load is lower. This is explained by the fact that spectrum is less occupied and it is easier for the re-allocation procedure to find available positions and re-configure the connection. In case of high load, the dynamicity becomes higher and the available options for re-allocation are fewer.

The indicated improvements are similar to the results presented in [11] where OSPF-TE is used for assisting the defragmentation, despite the fact that in [11] re-optimizations are initiated much more often (every 10 sec) and the work there employs k-shortest paths for connection establishment. Taking these facts into account our approach of using RSVP-TE is more efficient since we perform re-optimizations less often

resulting in lower signaling load in the control plane and fewer computational resources in the network as a whole.

Furthermore unlike the work in [11] we avoid delays in the decision process due to the time it takes OSPF to converge and rely on “fresher” information about the spectrum availability within the original path of the connection.

Table I presents the maximum and the average number of re-optimizations per channel which has had at least one re-optimization. Our results indicate no change across input loads for the maximum number of re-optimizations, which for both topologies equals 14 under the conducted simulation experiments. This can be linked to the similar level of dynamicity of the input traffic in both networks. With respect to the average number of re-optimizations the NSFnet has 7% higher average due to the fact that in this network more connections pass through less number of links (see the topology characteristics [14]) and a connection expiration would affect more connections on average which could potentially perform re-optimization.

TABLE I. AVERAGE AND MAXIMUM NUMBER OF RE-OPTIMIZATIONS PER RE-OPTIMIZED CONNECTION

Average number		Maximum number	
German 17	NSFnet	German 17	NSFnet
1,69	1,82	14	14

Compared to the results presented in [11], we achieve considerably lower amount of maximum and average re-optimizations, due to the employed re-optimization timer: we use 1 hour refresh timer, whereas the authors in [11] re-optimize every 10 seconds. Considering the achieved similar

performance and the fact that no OSPF-TE updates are used in our case, it can be concluded that using RSVP-TE refresh procedure for defragmentation optimization holds a considerable value, especially from a signaling overhead perspective

V. CONCLUSIONS

In this work we present a spectrum de-fragmentation method based on a modified RSVP-TE refresh procedure and show between 3% and 25% improvement in connection blocking probability in GMPLS based flexible optical networks. By using RSVP-TE refresh messages we collect the necessary information to re-allocate channels with only few changes in the RSVP-TE signaling procedure. The outcome is a reduced fragmentation which translates into a decreased connection blocking percentage.

Furthermore, our method does not rely on OSPF-TE link state advertisements, which reduces the control plane overhead and avoids a common drawback of taking decisions based on outdated routing information due to long OSPF-TE convergence times.

REFERENCES

- [1] R. W. Tkach "Scaling optical communications for the next decade and beyond" Bell Labs Technical Journal, vol. 14, no. 4, pp.3 – 9, Feb. 2010.
- [2] ITU-T G.694.1 Recommendation "Spectral grids for WDM applications: DWDM frequency grid".
- [3] F. Zhang, Y. Lee, O. G. de Dios, R. Casellas, D. Ceccarelli, X. Zi, J. Han, F. J. Arribas, "Framework for GMPLS and PCE Control of Spectrum Switched Optical Networks", IETF draft 2013.
- [4] I. Turus, J. Kleist, A. F. Manolova, L. Dittmann, "Evaluation of Strategies for Dynamic Routing Algorithms in Support of Flexible-Grid based GMPLS Elastic Optical Networks", in Proc. 39th Eur. Conf. Opt. Commun., London, United Kingdom, Sept. 2013, pp. 1-3. Paper We.3.E.5.
- [5] L. Liu, R. Casellas, R. Martinez, R. Munoz "Control plane techniques for elastic optical networks: GMPLS/PCE vs OpenFlow", IEEE Globecom, pp. 352 – 357, Saitama, Japan, Dec. 2012.
- [6] R. Munoz, R. Casellas, R. Martinez "Dynamic distributed spectrum allocation in GMPLS-controlled elastic optical networks", in Proc. 37th Eur. Conf. Opt. Commun., Geneva, Switzerland, Sept. 2011, pp. 1-3, Paper Tu.5.K.4.
- [7] O. Gerstel, M. Jinno, A. Lord, S. J. Ben Yoo, "Elastic Optical Networking: A New Dawn for the Optical Layer?" IEEE Comm. Mag., vol. 50, no. 2, pp. S12-S20, Feb 2012.
- [8] T. Takagi, H. Hasegawa, K. Sato, "Disruption minimized spectrum defragmentation in elastic optical path networks that adopt distance adaptive modulation", in Proc. 37th Eur. Conf. Opt. Commun., Geneva, Switzerland, Sept. 2011, pp. 1-3, Paper Mo.2.K.3.
- [9] F. Cugini, G. Meloni, F. Fresi et al., "Push-Pull defragmentation without traffic disruption in flexible grid optical networks" Journal of Lightwave Technology, vol. 31, no. 1, pp.125 – 133, Jan. 2013.
- [10] X. Wang, I. Kim, Q. Zhang, P. Paparao, M. Sekiya, "A hitless defragmentation method for self-optimizing flexible grid optical networks", in Proc. 38th Eur. Conf. Opt. Commun., Amsterdam, Netherlands, Sept. 2012, pp. 1-3, P.5.04.
- [11] D. Siracusa, A. Broglio, A. Zanardi, E. Salvadori, G. Galimberti, D. La Fauci, "Hitless Network Re-Optimization to Reduce Spectrum Fragmentation in Distributed GMPLS Flexible Optical Networks", in Proc. 39th Eur. Conf. Opt. Commun., London, United Kingdom, Sept. 2013, pp. 1-3, P.5.17.
- [12] R. Braden, L. Zhang, S. Berson, S. Herzog, S. Jamin, "Resource Reservation protocol – Version 1 Functional Specification". IETF Request for Comments 2205, September 1997.
- [13] OPNET Modeler, Riverbed Technology, <http://www.opnet.com>.
- [14] R. Hulsermann, S. Bodamer, M. Bary, A. Betker, C. Gauger, M. Jager, M. Kohn, J. Spath, "A set of typical Transport Network Scenarios for Network Modelling", ITG Fachbericht, Issue 182, pp. 65-72, 2004.

Bibliography

- [1] The Climate Group (GeSI), “SMART 2020: Enabling the low carbon economy in the information age”, London, UK, June 2008, [online] <http://smart2020.org/>
- [2] Celtic Elastic Optical Networks (EO-Net) Project, [online] <http://celtic-eonet.eu>
- [3] Cisco Virtual Networking Index (VNI) “The Zettabyte Era: Trends and Analysis”, June 2014, [online] http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/VNI_Hyperconnectivity_WP.html
- [4] NORDUnet traffic statistics “Traffic with customers”, September 2014, [online] <http://stats.nordu.net/stat-q/r-all?q=all&name=Customers>
- [5] CNET News, “Netflix reaches streaming traffic agreement with Comcast”, February 2014, [online] <http://www.cnet.com/news/netflix-reaches-streaming-traffic-agreement-with-comcast/>
- [6] C. Lange, O. Bonnes, and N. Leder, “Operator Perspective on Broadband Network Traffic Evolution,” in Proc. of 38th Eur. Conf. on Optical Commun. (ECOC ‘2012), (Amsterdam, Neth., 2012), paper Mo.2.D.1.
- [7] J.-K. K. Rhee, “Green IP over WDM Network Design Considering Energy-Load Proportionality,” in Proc. of International Conference on Computing, Networking and Communications (ICNC), February 2012, Hawaii, USA.
- [8] NORDUnet Network map, [online] <http://nordu.net/content/nordunet-network-map>
- [9] Y. Ben, O. Gerstel, M. Jinno and A. Lord “Elastic optical networking: A new dawn for the optical layer?,” IEEE Commun. Mag., vol. 50, no. 2, pp. S12-S20, February 2012.
- [10] E. Lach and W. Idler, “Modulation formats for 100G and beyond,” Journal of Optical Fiber Technology, vol. 17, no. 5, pp. 377-386, August 2011.
- [11] S. Gringeri, E. B. Basch and T. J. Xia, “Technical Considerations for Supporting Data Rates Beyond 100Gb/s,” IEEE Communications Magazine, vol. 50, no. 2, pp. s21-s30, February 2012 .
- [12] C. Rottondi, M. Tornatore and G. Gavioli, “Optical Ring Metro Networks With Flexible Grid and Distance-Adaptive Optical Coherent Transceivers,” Bell Labs Technical Journal, vol. 18, no. 3, pp. 95-110, 2013.
- [13] International Telecommunication Union, Telecommunication Standardization Sector, “Spectral Grids for WDM Applications: DWDM Frequency Grid,” ITU-T Rec. G.694.1, Edition 2, Feb. 2012, [online] <http://www.itu.int>
- [14] S. Luyi, F. Jinyi, and Y. Xiaohua “Forward Error Correction,” In Proc. of 4th International Conference on Computational and Information Sciences (ICCIS), pp. 37-40, 2012.

- [15] P. Layec, C. Dorize, O. Rival, F. Gioulekas, M. Birbas, C. Petrou, A. Vgenis, A. Rasmussen, and M. Karlsson, "D1.2: Report on modulation schemes and FEC performances and implementation for elastic WDM transmission systems," Deliv. Celt. Proj. CP7-006, EO-Net-WP1, 2012.
- [16] P. Layec, A. Morea, F. Vacondio, O. Rival and J-C. Antona, "Elastic Optical Networks: The Global Evolution to Software Configurable Optical Networks," Bell Labs Technical Journal, vol. 18., no. 3, pp. 133-151, 2013.
- [17] O. Rival, G. Villares, and A. Morea, "Impact of Inter-Channel Nonlinearities on the Planning of 25-100Gb/s Elastic Optical Networks," Journal of Lightwave Technology, vol. 29, no. 9, pp. 1326-1334, 2011.
- [18] O. Rival and A. Morea "Elastic optical networks with 25-100 G format-versatile WDM transmission systems," in Proc. of 15th OptoElectronics and Communications Conference (OECC 2010), Sapporo, Japan, July 2010.
- [19] R. Schmogrow, D. Hillerkuss, M. Dreschmann, M. Huebner, M. Winter, J. Meyer, B. Nebendahl, C. Koos, J. Becker, W. Freude, and J. Leuthold, "Real-Time Software-Defined Multiformat Transmitter Generating 64QAM at 28 GBd," IEEE Photonics Technology Letters, vol. 22, no. 21, pp. 1601-1603, 2010.
- [20] A. Bocoi, M. Schuster, F. Rambach, M. Kiese, C-A. Bunge, B. Spinnler, "Reach-dependent Capacity in Optical Networks enabled by OFDM," in Proc. of Optical Fiber Commun. Conf. (OFC'09) (San Diego, CA, 2009).
- [21] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, "Spectrum-Efficient and Scalable Elastic Optical Path Network: Architecture, Benefits, and Enabling Technologies," IEEE Communications Mag., vol. 47, no. 11, pp. 66-73, 2009.
- [22] A. Klekamp, O. Rival, A. Morea, R. Dischler, and F. Buchali, "Transparent WDM Network with Bitrate Tunable Optical OFDM Transponders," in Proc. of Optical Fiber Commun. Conf. (OFC '10) (San Diego, CA, 2010), paper NTuB5.
- [23] D. J. Geisler, N. K. Fontaine, R. P. Scott, T. He, L. Paraschis, O. Gerstel, J. P. Heritage, and S. J. B. Yoo, "Bandwidth Scalable, Coherent Transmitter Based on the Parallel Synthesis of Multiple Spectral Slices Using Optical Arbitrary Waveform Generation," Optics Express, vol. 19, no. 9, pp.8242-8253, 2011.
- [24] A. Morea, O. Rival, N. Brochier and E. Le Rouzic "Data rate adaptation for night-time energy savings in core networks," Journal of Lightwave Technology, vol 31, no. 5, pp. 779-785, March 2013.
- [25] G. H. Gho and J. M. Kahn, "Rate-adaptive Modulation and Coding for Optical Fiber Transmission Systems," Journal of Lightwave Technology, vol. 30, no. 12, pp. 1818-1828, 2012.
- [26] C. Dorize, O. Rival and C. Constantini, "Power scaling of LDPC decodes stage in long haul networks," in Proc. of Photonics in Switching Conf. (PS '12) (Ajaccio, Corsica, France, 2012), paper Th-S33-O07.

- [27] A. Rasmussen, M. P. Yankov, M. Berger, K. J. Larsen and S. Ruepp, "Improved Energy Efficiency for Optical Transport Networks by Elastic Forward Error Correction", *Journal of Optical Communications and Networking*, vol. 6, no. 4, pp. 397-407, April 2014.
- [28] D. Wang, Y. He, W. Ju, S. Huang, X. Li, B. Guo, J. Zhang and W. Gu "Contentionless ROADM architecture and extension for control plane in elastic optical path network," *Conference on Network Architectures, Management and Applications IX, SPIE-INT SOC Optical Engineering*, vol. 8310, pp. 83101T, 2011.
- [29] S. Frisken, G. Baxter, D. Abakoumov, H. Zhou, I. Clarke and S. Poole, "Flexible and Grid-less Wavelength Selective Switch using LCOS Technology," in *Proc. of Optical Fiber Commun. Conf. (OFC'11)* (Los Angeles, CA, 2011).
- [30] G. Shen, Q. Yang, "From Coarse Grid to Mini-Grid to Gridless: How much can Gridless Help Contentionless?," in *Proc. of Optical Fiber Commun. Conf. (OFC'11)* (Los Angeles, CA, 2011).
- [31] A. Morea, J. Renaudier, T. Zami, A. Ghazisaeidi and O. B.-Pardo. "Throughput Comparison Between 50-GHz and 37.5-GHz Grid Transparent Networks," invited to *Journal of Optical Communications and Networking*, vol. 7, no. 2, pp. A293-A300, 2015.
- [32] S. Syed, R. Rao, M. Sosa and B. Lu, "A Framework for control of Flex Grid Networks," *IETF Network Working Group, Internet Draft*, April 2012.
- [33] O. Gonzales de Dios, R. Casellas, F. Zhang, X. Fu, D. Ceccarelli and I. Hussain, "Framework and Requirements for GMPLS based control of Flex-Grid DWDM networks," *IETF Network Working Group, Internet Draft*, August 2014.
- [34] T. Takagi, H. Hasegawa, K. Sato, "Disruption minimized spectrum defragmentation in elastic optical path networks that adopt distance adaptive modulation," in *Proc. of 37th Eur. Conf. Opt. Commun.*, Geneva, Switzerland, September 2011, pp. 1-3, Paper Mo.2.K.3.
- [35] F. Cugini, G. Meloni, F. Fresi et al., "Push-Pull defragmentation without traffic disruption in flexible grid optical networks," *Journal of Lightwave Technology*, vol. 31, no. 1, pp.125–133, January 2013.
- [36] X. Wang, I. Kim, Q. Zhang, P. Paparao, M. Sekiya, "A hitless defragmentation method for self-optimizing flexible grid optical networks," in *Proc. of 38th Eur. Conf. Opt. Commun.*, Amsterdam, Netherlands, Sept. 2012, pp. 1-3, P5.04.
- [37] D. Siracusa, A. Broglio, A. Zanardi, E. Salvadori, G. Galimberti, D. La Fauci, "Hitless Network Re-Optimization to Reduce Spectrum Fragmentation in Distributed GMPLS Flexible Optical Networks," in *Proc. 39th Eur. Conf. Opt. Commun.*, London, United Kingdom, Sept. 2013, pp. 1-3, P.5.17.
- [38] L. Berger and D. Fedyk "Generalized MPLS (GMPLS) Data Channel Switching Capable (DCSC) and Channel Set Label Extensions," *Internet Engineering Task Force (IETF) Request For Comments (RFC) 6002*, October 2010.

- [39] D. Li, D. Ceccarelli and L. Berget “Link Management Protocol Behavior Negotiation and Configuration Modifications,” Internet Engineering Task Force (IETF) Request For Comments (RFC) 6898, March 2013.
- [40] D. Katz, K. Kompella and D. Yeung “Traffic Engineering (TE) Extensions of OSPF Version 2,” Internet Engineering Task Force (IETF) Request For Comments (RFC) 3630, September 2003.
- [41] K. Kompella and Y. Rekhter “OSPF Extensions in Support of Generalized Multi-Protocol Label Switching (GMPLS),” Internet Engineering Task Force (IETF) Request For Comments (RFC) 4203, October 2005.
- [42] “Telecommunications and information exchange between systems – Intermediate System to Intermediate System intra-domain routing information exchange protocol for use in conjunction with the protocol for providing connectionless-mode network service (ISO 8463),” ISO/IEC 10589:2002 Information Technology, Edition 2, 2002.
- [43] L. Berger “Generalized Multi-Protocol Label Switching (GMPLS) Signaling Resource ReserVation Protocol-Traffic Engineering (RSVP-TE) Extensions,” Internet Engineering Task Force (IETF) Request For Comments (RFC) 3473, January 2003.
- [44] B. Jamoussi, L. Andersson, R. Callon, R. Dantu, L. Wu, P. Doolan, T. Worster, N. Feldman, A. Fredette, M. Girish, E. Gray, J. Heinanen, T. Kilty and A. Malis “Constraint-Based LSP Setup using LDP,” Internet Engineering Task Force (IETF) Request For Comments (RFC) 3212, January 2002.
- [45] L. Andersson and G. Swallow, “The Multiprotocol Label Switching (MPLS) Working Group decision on MPLS signaling protocols”, Internet Engineering Task Force (IETF) Request For Comments (RFC) 3468, February 2003.
- [46] R. Rao, M. Sosa and A. Dhillon “TE extensions to OSPF for GMPLS control of Flex-Grid Networks,” IETF Network Working Group, Internet Draft, March 2014.
- [47] N. Sambo, F. Cugini, G. Bottari, P. Iovanna and P. Castoldi “Distributed Setup in Optical Networks with Flexible Grid,” in Proc. of 37th Eur. Conf. on Optical Commun. (ECOC ‘2011)” (Geneva, Switzerland, 2011).
- [48] R. Munoz, R. Casellas, R. Martinez, “Dynamic Distributed Spectrum Allocation in GMPLS-controlled Elastic Optical Networks,” in Proc. of 37th Eur. Conf. on Optical Commun. (ECOC ‘2011)” (Geneva, Switzerland, 2011).
- [49] R. Casellas, R. Munoz, J. M. Fabrega, M. S. Moreolo, R. Martinez, L. Liu, T. Tsuritani and I. Morita, “Design and Experimental Validation of a GMPLS/PCE Control Plane for Elastic CO-OFDM Optical Networks,” IEEE Journal on Selected Areas in Communications, vol. 31, no. 1, pp. 49-61, January 2013.
- [50] R. Munoz, R. Casellas, R. Martinez, L. Liu, T. Tsuritani and I. Morita, “Experimental evaluation of efficient routing and distributed spectrum allocation algorithms for GMPLS elastic networks,” in Proc. of 38th Eur. Conf. on Optical Commun. (ECOC ‘2012)” (Amsterdam, Neth., 2012).

- [51] G. Bernstein, Y. Lee, D. Li and W. Imajuku, "Routing and Wavelength Assignment Informaiton Encoding for Wavelength Switched Optical Networks," IETF Network Working Group, Internet Draft, May 2014.
- [52] JL. Le Roux, JP. Vasseur, Y. Ikejiri, R. Zhang, "OSPF Protocol Extensions for Path Computation Element (PCE) Discovery," Internet Engineering Task Force (IETF) Request For Comments (RFC) 5088, January 2008.
- [53] F. Zhang, X. Zhang, A. Farrel, O. G. de Dios and D. Ceccarelli "RSVP-TE Signaling Extensions in support of Flexible Grid", IETF Network Working Group, Internet Draft, February 2014.
- [54] A. Farrel, D. King, Y. Li and F. Zhang, "Generalized Labels for the Flexi-Grid in Lambda Switch Capable (LSC) Label Switching Routers", IETF Network Working Group, Internet Draft, February 2014.
- [55] T. Otani and D. Li, "Generalized Labels for Lambda-Switch-Capable (LSC) Label Switching Routers", Internet Engineering Task Force (IETF) Request For Comments (RFC) 6205, March 2011.
- [56] K. Christodopoulos, I. Tomkos and E. Varvarigos, "Routing and spectrum allocation in OFDM-based optical networks with elastic bandwidth allocation," IEEE Global Telecommunications Conference (GlobeCom) 2010, Miami, Florida, 2010.
- [57] K. Christodopoulos, I. Tomkos and E. Varvarigos, "Elastic bandwidth allocation in flexible ofdm-based optical networks," Journal of Lightwave Technology, vol. 29, no. 9, pp. 1354-1366, 2011.
- [58] K. Christodopoulos, I. Tomkos and E. Varvarigos, "Spectrally/bitrate flexible optical network planning", in Proc. of 36th Eur. Conf. on Optical Commun. (ECOC '2010)" (Torino, Italy, 2010).
- [59] M. Klinkowski and K. Walkowiak, "Routing and Spectrum assignment in Spectrum Sliced Elastic Optical Path Network," IEEE Communications Letters, vol. 15, no. 8, pp. 884-886, 2011.
- [60] Y. Wang, X. Cao and Q. Hu, "Routing and Spectrum Allocation in Spectrum-Sliced Elastic Optical Path Networks," in Communications (ICC), 2011 IEEE International Conference on Communications, IEEE, 2011, pp. 1-5.
- [61] S. Kosaka, H. Hasegawa, K. Sato, T. Tanaka, A. Hirano and M. Jinno, "Shared Protected Elastic Optical Path Network Design that Applies Iterative Re-optimization based on Resource Utilization Efficiency Measures," in Proc. of 38th Eur. Conf. on Optical Commun. (ECOC '2012)" (Amsterdam, Netherlands, 2012).
- [62] Y. Sone, A. Hirano, A. Kadohata, M. Jinno and O. Ishida, "Routing and Spectrum Assignment Algorithm Maximizes Spectrum Utilization in Optical Networks," in Proc. of 37th Eur. Conf. on Optical Commun. (ECOC '2011)" (Geneva, Switzerland, 2011).
- [63] T. Takagi, H. Hasegawa, K. Sato, Y. Sone, B. Kozicki, A. Hirano, and M. Jinno, "Dynamic routing and frequency slot assignment for elastic optical path networks that

adopt distance adaptive modulation,” in Proc. of Optical Fiber Commun. Conf. (OFC’11) (Los Angeles, CA, 2011).

[64] S. Thiagarajan, M. Frankel, and D. Boertjes, “Spectrum Efficient Super-Channels in Dynamic Flexible Grid Networks- A Blocking Analysis,” in Proc. of Optical Fiber Commun. Conf. (OFC’11) (Los Angeles, CA, 2011).

[65] K. Christodopoulos, I. Tomkos, and E. Varvarigos, “Dynamic bandwidth allocation in flexible OFDM-based networks,” in Proc. of Optical Fiber Commun. Conf. (OFC’11) (Los Angeles, CA, 2011).

[66] G. Meloni, F. Paolucci, N. Sambo, F. Cugini, M. Secondini, L. Gerardi, L. Poti, and P. Castoldi, “PCE architecture for flexible WSON enabling dynamic rerouting with modulation format adaptation,” in Proc. of 37th Eur. Conf. on Optical Commun. (ECOC ‘2011)” (Geneva, Switzerland, 2011).

[67] N. Sambo, F. Cugini, G. Bottari, G. Bruno, P. Iovanna, and P. Castoldi “Lightpath provisioning in wavelength switched optical networks with flexible grid,” in Proc. of 37th Eur. Conf. on Optical Commun. (ECOC ‘2011)” (Geneva, Switzerland, 2011).

[68] N. Sambo, F. Cugini, G. Bottari, P. Iovanna, P. Castoldi “Routing and Spectrum Assignment for Super-Channels in Flex-Grid Optical Networks,” Proc. 38th Eur. Conf. on Optical Commun. (ECOC ‘2012)” (Amsterdam, Neth., 2012).

[69] C. Politi, V. Anagnostopoulos, C. Matrakidia, A. Stavdas “Dynamic Flexi-grid OFDM Optical Networks,” in Proc. of 38th Eur. Conf. on Optical Commun. (ECOC ‘2012)” (Amsterdam, Netherlands, 2012).

[70] R. Casellas, R. Martinez, R. Munoz, L. Liu, T. Tsuritani, I. Morita, “Dynamic Provisioning via a Stateful PCE with Instantiation Capabilities in GMPLS-Controlled Flexi-grid DWDM Networks,” in Proc. of 39th Eur. Conf. on Optical Commun. (ECOC ‘2013)” (London, UK, 2013).

[71] S. Shen, W. Lu, X. Liu, L. Gong, Z. Hu, “Dynamic Advanced Reservation Multicast in Data Center Networks over Elastic Optical Infrastructure,” in Proc. of 39th Eur. Conf. on Optical Commun. (ECOC ‘2013)” (London, UK, 2013).

[72] Open Networking Foundation, “Software-Defined Networking: The New Norm for Networks,” White Paper, April 2012.

[73] Open Networking Foundation, [online] <https://www.opennetworking.org/>

[74] Open Networking Foundation, “OpenFlow-enabled Transport SDN,” White Paper, May 2014.

[75] Saurav Das, “Extensions to the OpenFlow Protocol in support of Circuit Switching,” Addendum to OpenFlow Protocol Specification (v1.0) – Circuit Switch Addendum, June 2010.

[76] D. Simeonidou, R. Nejabati and M. P. Channegowda, “Software Defined Optical Networks Technology and Infrastructure: Enabling Software-Defined Optical

Network Operations,” in Proc. of Optical Fiber Commun. Conf. (OFC’13) (Anaheim, CA, 2013).

[77] T. Szyrkowiec et al. “Demonstration of SDN Based Optical Network Virtualization and Multidomain Service Orchestration,” 3rd European Workshop on Software Defined Networks (EWSN 2014), Budapest, Hungary.

[78] S. Gringeri, N. Bitar and T. Xia “Extending Software Defined Network Principles to Include Optical Transport”, IEEE Communications Magazine, vol. 51, no. 3, pp. 32-40, 2013.

[79] N. Amaya, S. Yan, M. Channegowda, B. R. Rofoee, Y. Shu, M. Rashidi, Y. Ou, G. Zervas, R. Nejabati, D. Simeonidou, B. J. Puttnam, W. Klaus, J. Sakaguchi, T. Miyazawa, Y. Awaji, H. Harai and W. Wada, “First demonstration of software defined networking (SDN) over space division multiplexing (SDM) optical networks,” Postdeadline, 39th Eur. Conf. on Optical Commun. (ECOC ‘2013)” (London, UK, 2013).

[80] R. Munoz, R. Casellas, R. Martinez, L. Liu, T. Tsuritani and I. Morita, “OpenSlice: an OpenFlow-based control plane for spectrum sliced elastic optical path networks,” Optics Express, vol. 21, no. 4, pp. 4194-4204, 2013.

[81] M. Jinno, Y. Sone, H. Takara, A. Hirano, K. Yonenaga and S. Kawai, “IP traffic offloading to elastic optical layer using multi-flow optical transponder,” in Proc. of 37th Eur. Conf. on Optical Commun. (ECOC ‘2011)” (Geneva, Switzerland, 2011).

[82] “NOX: an OpenFlow controller,” [online] <http://www.noxrepo.org/nox/about-nox/>

[83] L. Liu, T. Tsuritani, I. Morita, R. Casellas, R. Martinez and R. Munoz, “An integrated stateful PCE / OpenFlow controller for the control and management of flexi-grid optical networks,” in Proc. of Optical Fiber Commun. Conf. (OFC’13) (Anaheim, CA, 2013).

[84] X. Wang, H. Zheng, Y. Lin, Y. Zhao, R. He, H. Chen, J. Zhang and Y. Ji, “Experimental performance evaluation of software defined networking (SDN) based data communication networks for large scale flexi-grid optical networks,” Optics Express, vol. 22, no. 8, pp. 8538-8547, 2014.

[85] R. Casellas, R. Martinez, R. Munoz, W.-R. Peng, T. Tsuritani, I. Morita, L. Liu and S. J. B. Yoo, “Design and performance evaluation of an OpenFlow-based control plane for software defined elastic optical networks with direct-detection optical OFDM (DDO-OFDM) transmission,” Optics Express, vol. 22, no. 1, pp. 30-40, 2014.

[86] R. Tucker and K. Hinton, “Energy-Efficiency Networking”, Course Material, Optical Fiber Commun. Conf. (OFC’14) (San Francisco, CA, 2014).

[87] C. Lange, D. Kosiankowski, A. Gladisch and R. Weidmann, “Energy Consumption of Telecommunication Networks and Related Improvements Operations,” IEEE Journal on Selected Topics in Quantum Electronics, vol. 17. No. 2, pp. 285-295, 2011.

- [88] ITU Recommendation: L.1310, "Energy efficiency metrics & measurement methods for telecommunications equipment," June 2012.
- [89] J. Charzinski, M. Menth and R. Martin "Capacity overprovisioning for networks with resilience requirements," in Proc. of Conference on Applications, technologies, architectures, and protocols for computer communications (SIGCOMM '06), New York, NY, 2006.
- [90] A. Morea, J. Perello and S. Spadaro, "Traffic variation-aware networking for energy efficient optical communications," in Proc. of 17th International Conference on Optical Networking Design and Modeling (ONDM) Brest, France, 2013.
- [91] Amsterdam Internet Exchange, [online] <http://amx.ix.net/statistics/>
- [92] R. Hulsermann, C. Lange, D. Kosiankowski and A. Gladisch "Analysis of the Energy Efficiency in IP over WDM Networks with Load-Adaptive Operation," in Proc. of Photonic Networks, Paper 31, Leipzig, May 2011.
- [93] A. Chiu, R. Doverspike, G. Li and J. Strand, "Restoration Signaling Protocol Design for Next-Generation Optical Network," in Proc. of Optical Fiber Commun. Conf. (OFC'09) (San Diego, CA, 2009).
- [94] I. Cerutti, P. Castoldi and N. Sambo, "Sleeping link selection for Energy-Efficient GMPLS Networks", Journal of Lightwave Technology, vol. 29, no 15, pp. 2292-2298, 2011.
- [95] A. Morea, O. Rival, D. Verchere, S. Spadaro, J. Perello and F. Agraz, "Power management of optoelectronic interfaces for dynamic optical networks," in Proc. of 37th Eur. Conf. on Optical Commun. (ECOC '2011)" (Geneva, Switzerland, 2011), paper We.8.K.3.
- [96] J. Perello, S. Spadaro, A. Morea and M. Tornatore "Link. Vs. Opto-Electronic Device Sleep Mode Approaches in Survivable Green Optical Networks," in Proc. of Optical Fiber Commun. Conf. (OFC'13) (Anaheim, CA, 2013).
- [97] A. Morea, G. Rizelli and M. Tornatore "On the energy and cost trade-off of different energy-aware network design strategies," in Proc. of Optical Fiber Commun. Conf. (OFC'13) (Anaheim, CA, 2013), paper OM3A.4.
- [98] OPNET Modeler, Riverbed Technology, [online] <http://www.opnet.com>
- [99] M. Christian, S. De Maesschalck, M. Jaeger, B. Mikac, R. Inkret, J. Derkacz, P. Demeester, M. Pickavet, I. Lievens and D. Colle, "Pan-European optical transport networks: An availability-based comparison," Photonic Network Communications, vol. 5, no. 3, pp. 203-225, May 2003.
- [100] R. Hulsermann, S. Bodamer, M. Barry, A. Betker, C. Gauger, M. Jager, M. Kohn and J. Spath, "A set of typical Transport Network Scenarios for Network Modelling," ITG Fachbericht, no. 182, pp. 65-71, 2004.
- [101] J. Wang, S. Ruepp, A. Manolova and L. Dittmann "Energy-Efficient Routing in GMPLS Network", In Proc. of OPNETWORK 2011, Washington, D.C., 2011.

List of Acronyms

ACK	Acknowledgement
ALU	Alcatel-Lucent
AoD	Architecture on Demand
API	Application Programming Interface
ASIC	Application-Specific Integrated Circuit
BE	Best Effort
BER	Bit Error Rate
BoD	Bandwidth on Demand
BS	Base Station
BV-WSS	Bandwidth Variable - WSS
CAGR	Compound Annual Growth Rate
CF	Central Frequency
CFG	Central Frequency Granularity
CO-OFDM	Coherent Optical - OFDM
COS	Class of Service
COST	European Cooperation in Science and Technology
CR-LDP	Constraint-based Routing Label Distribution Protocol
CS	Channel Spacing
DDO-OFDM	Direct-Detection Optical - OFDM
DSP	Digital Signal Processing
DT	Deutsche Telekom
DTU	Danmarks Tekniske Universitet
DWDM	Dense Wavelength Division Multiplexing
EON	Elastic Optical Networks
ERO	Explicit Route Object
ESS	Elementary Spectrum Slots
FEC	Forward Error Correction
FPGA	Field-Programmable Gate Array

FSM	Finite State Machine
FTTH	Fiber To The Home
GbE	GigaBit Ethernet
GHG	GreenHouse Gas
GMPLS	Generalized Multi-Protocol Label Switching
HD	High Definition
ICT	Information and Communications Technologies
IETF	Internet Engineering Task Force
IP	Internet Protocol
IS-IS	Intermediate System to Intermediate System
ISP	Internet Service Provider
ITU-T	International Telecommunication Union - Telecommunication
IX	International Exchange
LCOS	Liquid Crystal on Silicon
LDPC	Low Density Parity Check
LER	Label Edge Router
LM	Light Manager
LMP	Link Management Protocol
LSA	Link State Advertisement
LSP	Label Switched Path
LTE	Long Term Evolution
MCF	Multi-core Fibers
MEM	Micro-Electro-Mechanical system
MF	Modulation Format
MIMO	Multiple-Input Multiple-Output
MIT	Mean Inter-arrival Time
MOTP	Multi-flow Optical Transponder
MPLS	MultiProtocol Label Switching
NAT	Network Address Translation
NREN	National Research and Education Network

NRZ	Non Return to Zero
NSF	National Science Foundation
OE	Optoelectronic device
OF	OpenFlow
OFDM	Orthogonal Frequency-Division Multiplexing
OFDM	Orthogonal Frequency Division Multiplexing
ONF	Open Networking Foundation
OOK	On-Off Keying
OPEX	Operational Expenditure
OSPF-TE	Open Shortest Path First - Traffic Engineering
OTN	Optical Transport Network
OXC	Optical Cross Connects
PCE	Path Computation Element
PCEP	Path Computation Element Protocol
PMD	Polarization Mode Dispersion
PON	Passive Access Network
PS	Photonic Service
QAM	Qadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
R&E	Resource and Education
RMSA	Routing Modulation and Wavelength Assignment
RO	Regenerator Object
ROADM	Reconfigurable Add-Drop Multiplexer
RSVP-TE	Resource Reservation Protocol - Traffic Engineering
RWA	Routing and Wavelength Assignment
RZ	Return to Zero
SCC	Spectrum Continuity Constraint
SDM	Space Division Multiplexing
SDN	Software Defined Networks

SLA	Service Level Agreements
SP-QPSK	Single Polarization - Binary Phase Shift Keying
SR	Symbol-Rate
SSC	Spectrum Switch Capable
SSG	Spectrum Slice Granularity
SSON	Spectrum Switched Optical Networks
SSW	Spectrum Slice Width
STM	Synchronous Transport Module
TLV	Type Length Value
TRX	Transponder
VDSL	Very High bitrate Digital Subscriber Line
VLAN	Virtual Local Area Network
VoD	Video on Demand
WDM	Wavelength Division Multiplexing
WSON	Wavelength Switched Optical Networks
WSS	Wavelength Selective Switch